EMBEDDED NAVIGATION SYSTEM OF MECHATRONICS ROBOT BY FUZZY CONTROL ALGORITHM

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Abstract - With the development of mechatronics robot intelligence and autonomy, automatic obstacle avoidance and path planning has become the core of the current robot navigation system research. This research aims to solve the problems of complex path planning and poor parameter strain in ultrasonic array navigation systems. Firstly, the research status of the mobile robot is introduced, and a new embedded navigation system based on ultrasonic array technology is designed. Then, the fuzzy control algorithm is introduced, and a new Positive/Negative (P/N) local path planning algorithm based on fuzzy control is proposed. The normal rule is used to make the robot move toward the target point, in which the robot avoids obstacles through negative rules. The complexity of the fuzzy system is reduced through binary negative rules. Then, the precise output is obtained through the path decision formula to realize the local path planning system of the mechatronic robot. Finally, the simulation results verify the effectiveness of the improved algorithm. Based on the joint simulation experiment platform of Simulink and Robot Operating System (ROS), the excellent performance of the proposed embedded navigation system has been verified. The new P/N local path planning algorithm of fuzzy control can make the running track more accurate and smoother by optimizing the path. The new embedded navigation system can provide theoretical analysis and practical reference for developing an electromechanical robot navigation system.

Keywords: Fuzzy control; Mechatronics; Robot; Navigation system; Path planning.

1. Introduction

Since the 20th century, the progress of science and technology, especially the rapid development of information technology, has made robot technology more and more important in modern industry. It has become an important symbol to measure the level of the modern manufacturing industry and scientific and technological development [1]. Robots play an important role in today's industry, agricultural production, and life, as well as in many fields, and have a very broad development prospect. Currently, the development direction of mechatronics technology is mainly to promote robots’ digitalization, intelligence, and automation. Mobile robot belongs to an important branch of mechatronics robot. It integrates the functions of environmental information perception, operation dynamic programming and decision, behavior control and execution, and covers several technologies such as robot motion modeling and analysis, intelligent motion control, autonomous navigation, and trajectory tracking [2]. The core technology of mobile robots must be the autonomous navigation system, especially the automatic obstacle avoidance and local path planning technology. At present, in order to reduce costs, industrial robots do not use laser, radar, and other obstacle avoidance technologies and mature sensors with path planning technology for navigation. Generally, they use ultrasonic sensors with simple information processing, high speed, and low cost. However, due to its narrow beam angle, the mobile robot has a small detection range and blind areas for detection, which cannot fully ensure the smoothness and safety of robot movement [3]. On the other hand, because the mobile robot's current path planning algorithm system runs through the designed motion path, real-time and obstacle avoidance are not ideal. Therefore, robots' new path planning and obstacle avoidance technology will have very important practical application value.

Currently, more and more attention is paid to the research of robot navigation systems. Adamkiewicz et al. (2022) proposed an algorithm for positioning using an onboard camera for navigating a robot in a three-dimensional (3D) environment represented as a neural radiation field. They introduced trajectory optimization algorithms to avoid collisions with high-density
areas in the neural radiation field and demonstrated an omnidirectional ground robot navigating a church. The robot can be reoriented to adapt to narrow gaps [4]. Hu et al. (2021) introduced a new simulation algorithm for mobile robots to effectively learn how to navigate in the rough terrain environment of the real world. Experiments verified that the robot successfully performs point-to-point navigation from any starting point and target position when crossing rough terrain and performs better in terms of success rate, cumulative travel distance, and time in a 3D rough terrain environment [5]. Kahn et al. (2021) used self-labeled non-policy data collected in the real environment for training the mobile robot navigation system based on end-to-end learning. The system does not require any simulation or manual supervision, can be combined with terrain preferences, extended to new environments, and continue to improve autonomically by collecting more data [6]. Yao et al. (2021) proposed to convert self-intersecting or simple closed expected paths into non-self-intersecting and corresponding unbounded paths in high-dimensional space and constructed a singularity-free guide vector field in high-dimensional space. Thus, the global convergence is achieved to the high dimensional expected path, and the projection on the low dimensional subspace converges to the physical expected path [7]. Liu et al. (2021) provided a self-improving lifelong learning framework for mobile robots navigating in different environments. They improved the mobile robot’s navigation behaviour and retained the robot’s ability to navigate in the previous environment after learning in the new environment. Experiments show that robots have limited memory and computing budgets [8].

The innovation is that the Fuzzy Control Algorithm (FCA) is used in the robot navigation system. An improved Positive/Negative (P/N) local path planning algorithm and a new embedded navigation system are proposed based on ultrasonic array technology. Firstly, the concept and system structure of the robot navigation system is introduced. Then, the robot obstacle avoidance detection of the ultrasonic array and the existing problems are described. Next, the principle of the fuzzy control system is summarized. Then, an electromechanical robot navigation system, including a mobile robot’s ultrasonic array obstacle avoidance system and local path planning algorithm, is designed. Finally, the simulation experiment and result analysis of mobile robot local path planning is carried out.

2. Method
2.1 Overview of the Robot Navigation System

In general, mechatronics robots mainly comprise a robot body structure, acquisition structure of environment sensor information, intelligent trajectory planning system, and other parts. The mobile robot relies on sensors to collect and process environmental information and controls the robot’s behavior to achieve automatic navigation [9]. The structure of the entire navigation system is shown in Figure 1:

![Figure 1: Structure of robot navigation system](image_url)

In Figure 1, the navigation system can be considered a closed-loop system. The working process is as follows: the sensors on the robot perceive the external environment information, and the obtained information is transmitted to the central controller for information processing. Then, after the corresponding algorithm is processed, the processing results are converted into control commands and sent to the robot motion control board. Finally, the control algorithm is used to control the specific speed and direction of the robot, realizing the closed-loop control of the robot operation [10]. Path planning refers to the physical environment with obstacles, and the robot can automatically find a suitable running path from the starting point to the destination. The running process must ensure that it cannot hit obstacles in the path. There are three main problems for the robot to realize proper path planning. Firstly, the robot can successfully reach the target location. Secondly, the robot must safely avoid obstacles in the process of movement. The third is to improve sports efficiency as much as possible in accurately completing sports tasks [11].

The current path planning, according to the different situations of the robot, can be divided into global path planning with known environmental information. The local path planning in real-time depends on the information collected by sensors and the unknown environment information. The local path planning is planned in an unknown environment, and the obstacle environment may change dynamically. Therefore, the feasibility of path planning should be considered, and real-time planning should be guaranteed.
2.2 Robot Obstacle Avoidance Detection based on the Ultrasonic Array

In order to realize the local path planning of robots, obstacle avoidance technology is the premise of successful motion. The ultrasonic sensor array is widely used in robot obstacle avoidance technology due to its advantages, such as simple information processing, fast speed, and low cost. However, the traditional ultrasonic sensor array mainly has problems such as large detection blind areas and unreasonable detection range, which cannot fully guarantee the safety of robot movement [12]. In view of the shortcomings of the previous ultrasonic array, this research especially uses six ultrasonic sensors to design a new type of ultrasonic array for the robot navigation system, which can realize the detection of the minimum environment blind area in the front and on the left and right sides of the robot. The detection area of the ultrasonic array designed is shown in Figure 2:

![Figure 2: The area detected by the ultrasonic array](image)

In Figure 2, the robot’s left side is mainly detected by sensors 1 and 2. The outermost two sensors detect areas 6, 8, 11, and 12. The inward sensors 3 and 4 detect areas 5, 9, 10, and 13. The front area of the robot is jointly detected by the innermost 5 and 6 ultrasonic sensors. Although the two small black areas are not detected, they will not affect normal operation, and the obstacles in the remaining areas will not affect the robot’s advance and left and right turns.

The new ultrasonic array constructed can eliminate the large area of detection blind area existing in traditional ultrasonic sensors and can also avoid misoperation caused by the excessive detection range of obstacle avoidance area.

Additionally, this research combines the obstacle avoidance method based on dichotomy, which reduces the false obstacle avoidance and secondary obstacle avoidance phenomenon during the operation and realizes the accurate obstacle avoidance of the robot. In order to simplify the process of robot acquiring environmental information, the control system can not only accurately detect static obstacles, improving the real-time performance of robot obstacle avoidance control [13]. The specific control process when the robot moves forward is shown in Figure 3:

![Figure 3: Control flow of ultrasonic array detection range](image)

In Figure 3, when the robot is in the forward state, to improve the system control’s real-time performance, the data collected by No. 3 and No. 4 ultrasonic sensors are read. Then, the dichotomy method is used to judge whether there are obstacles in front of the robot. If there are obstacles, other sensors are used to detect the obstacles on the left and right sides so as to determine the best obstacle avoidance path for the robot.

2.3 FCA

A fuzzy algorithm is the practical application of fuzzy mathematics in the field of robot operation control. Its principle does not require the accurate calculation of environmental information but relies on the summary of successful human operation methods. The local path planning designed by the navigation system is based on the fuzzy processing of the collected environmental information and then realized by corresponding fuzzy control rules [14]. The advantage is that there is no need to establish an accurate mathematical model, and it has an excellent effect in dealing with the path planning problem in uncertain and complex environments. The basic principle block diagram is shown in Figure 4:
means to control the robot to always move towards the target and shorten the running path as much as possible, mainly by strengthening the weight of normal rules to improve the adaptability of running parameters. The virtual repulsive force ensures that obstacles in the path are avoided to ensure the robot operation’s safety and simplify the complexity of fuzzy rules in the system by binarization. Finally, the accurate output is obtained through the path decision-making formula to carry out path planning [17]. The structure of the robot navigation system is shown in Figure 5:

In Figure 5, the hardware system is designed to realize multiple functions, such as automatic obstacle avoidance and remote operation of the mobile robot. Therefore, the embedded design idea is adopted in the system. The operating system and functional software are integrated into the computer hardware system, which is suitable for real-time and multi-task systems. Firstly, the sensors carried are used to sense the obstacle information of the robot’s running environment and make judgments. Then, the processed obstacle information is sent to the behavior fuzzy controller, where the logical judgment of obstacle avoidance and target-oriented action is realized. Secondly, the behavior information calculated by the fuzzy controller is transmitted to the next executive layer based on the behavior decision-making part. Finally, the experiment drives the robot to the destination according to the planned path. The information input of the fuzzy controller mainly includes the target point’s angle relative to the robot’s moving direction, the actual distance between them, and the steering angle of the current mobile robot. The robot model studied is to simulate a two-wheel differential robot, which will turn through angular velocity transformation while maintaining a certain linear speed. Therefore, the navigation system introduces a sign bit to strengthen

2.4 P/N Local Path Planning Algorithm with Improved Fuzzy Control

The local path planning design comprises route selection and obstacle avoidance. The shortest path to reach the target point is the best running route for the robot. Obstacle avoidance ensures the robot can reasonably avoid obstacles in the running path. Therefore, a P/N local path planning algorithm with improved fuzzy control is proposed. "Positive"
the weight of normal rules in the running path decision-making part. The mechatronic robot can avoid obstacles and, make the next turn and run as far as possible toward the destination.

This research focuses on achieving intelligent navigation of mechatronic integrated robots in complex environments, with special attention to the practical navigation performance of the local path planning system when facing complex-shaped obstacles, a large number of obstacles, and regular scenarios. Firstly, by introducing ultrasonic array technology, a novel embedded navigation system is designed to address issues of complex path planning and insufficient parameter adaptability in existing robot navigation systems. In practice, the local path planning system of the mechatronic integrated robot fully utilizes ultrasonic array technology to provide real-time environmental information by perceiving the distribution of obstacles in the surroundings. Confronted with obstacles of complex shapes, this system can effectively analyze the geometric features of obstacles and employ FCA for flexible path planning. Additionally, when dealing with a large number of obstacles, the system, through fuzzy control’s P/N local path planning algorithm, enables the robot to intelligently avoid obstacles and find the optimal passage. Specifically, the application of positive rules guides the robot toward the predetermined target point, ensuring the overall goal tracking of the navigation system. When encountering obstacles, negative rules, implemented through FCA, intelligently enable obstacle avoidance, ensuring the safety and stability of the robot. Adopting binary negative rules specifically reduces the complexity of the fuzzy system, enhances real-time performance, and enables the robot to make decisions more quickly. In practical navigation, this system ensures more accurate and smooth local path planning for the robot through precise output from the path decision formula. Simulation experiment results validate the effectiveness of the improved algorithm on the joint simulation platform of Simulink and the Robot Operating System (ROS).

3. Results and Discussion
3.1 Setting of Simulation Experiment Environment

In order to verify the performance of the improved fuzzy control P/N local path planning algorithm, three simulation experiments are carried out on the MatlabR2018a software. The map scene takes the form of a grid graph. Obstacles in the path are marked black. A white area represents the free space that the robot can move. The coordinates of the grid graph are refined to 10 times to improve the accuracy of simulation environment modeling. The simulation experiment conditions are set as follows: the distribution of obstacles in the map is unknown. The particle simulation robot simulates the differential movement in the process of movement. The robot can detect obstacles on the front and left and right sides in real-time, thus obtaining the coordinates of the current robot’s starting point and destination, as well as its own real-time coordinates, running speed, and angular speed. Its initial heading angle parameter is set to 45°.

3.2 Local Path Planning Simulation and Result Analysis

In order to verify the performance of the traditional algorithm track and the improved algorithm track, the simulation experiment is conducted under the conditions of large and small angular velocity. The specific experimental results are shown in Figure 6:

![Figure 6: Comparison results of simulation experiments](image)

In Figure 6, the solid blue line refers to the trajectory planned by the traditional navigation algorithm. In Figure 6(a), when the running angular velocity of the mechatronic robot is too large, it will cause severe vibration when it is moving toward the destination. The robot’s navigation system will constantly adjust its position and posture to face the destination. When the angular velocity is set too high, each direction adjustment will not be able to accurately face the target, resulting in the reciprocating motion of the robot. In Figure 6 (b), when the angular velocity of the robot is too small, it will lead to the control of the linear and angular velocity in the next step of movement after avoiding obstacles so that the final running path becomes a larger arc, which leads to redundant running tracks. The robot’s angular velocity in the traditional navigation system will seriously impact the path-planning effect. In Figure 6, the red dotted line is the track of the improved local path planning algorithm. The results show that this navigation system can make the robot plan a suitable motion path to the destination without vibration, thus reducing the...
running time. Additionally, to preliminarily verify the algorithm's effectiveness in the real-life environment, a simulation experiment is conducted to simulate the real-life scene. The specific experimental results are shown in Figure 7:

![Simulation experiment results of simulating real scenes](image)

**Figure 7: Simulation experiment results of simulating real scenes**

In Figure 7, the new P/N local path planning can carry out suitable local planning in the simulation experiment simulating the real scene. The new path planning can achieve normal obstacle avoidance behavior in the real-time simulation of real-life scenarios.

### 3.3 Simulation Experiment and Result Analysis of Robot Local Path Planning

ROS, a software specialized in robot research, can simulate a high-fidelity model with a physical engine. In order to verify the effectiveness of the algorithm in the actual system, this chapter uses this software to build a joint simulation experiment platform for Simulink and Gazebo to communicate, which solves the problems of difficult information interaction and complex program migration in previous cross-system experiments. The detailed trajectory and operation parameter analysis is shown in Figure 8:

![Path planning process of the robot](image)

**Figure 8: Path planning process of the robot**

**Figure 8(a)** is the initial scene of the experiment. **Figure 8(b)** is the target point after obstacle avoidance. The white area in **Figure 8(b)** represents the obstacle avoidance process. In contrast, a complete obstacle avoidance process refers to the process from the first encounter with an obstacle to the complete separation from the obstacle. Therefore, the robot path planning in the simulation experiment can be divided into three obstacle avoidance processes. The detailed analysis results of the robot operation process are shown in Figure 9:

![Operating parameters of the robot reaching the target point](image)

**Figure 9: Operating parameters of the robot reaching the target point**

The speed change area in Figure 9 corresponds to the three obstacle avoidance scenarios in Figure 8. When each obstacle avoidance behavior of the robot ends, the heading angle will trigger the weight of the enhanced normal rule to move toward the destination. In the obstacle avoidance process, the robot will have the phenomenon of heading angle fluctuation because the robot will make decisions and then move in combination with the relative position of the target point. The performance of the local path planning system for mechatronic integrated robots in the presence of obstacles with complex shapes is illustrated in Table 1. The system's performance under a large number of obstacles is presented in Table 2. Table 3 outlines the system's performance under regular obstacles.

<table>
<thead>
<tr>
<th>Table 1: System Performance under Complex-Shaped Obstacles</th>
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<tbody>
<tr>
<td>(a) Initial scene of simulation experiment</td>
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<tr>
<td>(b) Reach the target point after avoiding obstacles for three times</td>
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</table>

![Initial scene of simulation experiment](image)

![Reach the target point after avoiding obstacles for three times](image)

| (a) Robot running track |
| (b) Relevant angle parameters |

![Robot running track](image)

![Relevant angle parameters](image)
Embedded Navigation System of Mechatronics Robot by Fuzzy Control Algorithm

<table>
<thead>
<tr>
<th>Time step</th>
<th>Robot X coordinate</th>
<th>Robot Y coordinate</th>
<th>Obstacle 1 position</th>
<th>Obstacle 2 position</th>
<th>Improve algorithm path</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(3,4,5)</td>
<td>(1,2,3)</td>
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<tr>
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<td>1</td>
<td>2</td>
<td>(3,4,5)</td>
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<tr>
<td>2</td>
<td>2</td>
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<td>(3,4,5)</td>
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<tr>
<td>3</td>
<td>3</td>
<td>6</td>
<td>(3,4,5)</td>
<td>(1,2,3)</td>
<td>(3,6)</td>
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</tbody>
</table>

In Table 1, under the scenario of obstacles with complex shapes, the improved algorithm exhibits outstanding performance. The robot successfully navigates around obstacles, moving towards the target point along the anticipated path. The improved algorithm dynamically updates the robot's path at each time step, ensuring adaptability to complex environments and effectively avoiding multiple obstacles.

Table 2: System Performance under a Large Number of Obstacles

<table>
<thead>
<tr>
<th>Time step</th>
<th>Robot X coordinate</th>
<th>Robot Y coordinate</th>
<th>Obstacle 1 position</th>
<th>Obstacle 2 position</th>
<th>Improve algorithm path</th>
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<tbody>
<tr>
<td>0</td>
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<td>(2,2)</td>
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<td>(2,2)</td>
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<td>(3,3)</td>
<td>(3,6)</td>
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</table>

In Table 2, within a scenario involving a large number of obstacles, the improved algorithm similarly demonstrates robust performance. The robot exhibits flexibility in choosing obstacle-avoidance paths when confronted with complex environments, thereby successfully reaching the target point. The improved algorithm consistently updates the path in real-time at each time step, enabling the robot to effectively respond to dense obstacle scenarios.

Table 3: System Performance under Regular Obstacles

<table>
<thead>
<tr>
<th>Time step</th>
<th>Robot X coordinate</th>
<th>Robot Y coordinate</th>
<th>Obstacle 1 position</th>
<th>Obstacle 2 position</th>
<th>Improve algorithm path</th>
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<tbody>
<tr>
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<td>(1,1)</td>
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<td>(1,1)</td>
<td>(2,2)</td>
<td>(3,4)</td>
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</table>

In Table 3, the improved algorithm has also achieved satisfactory results under the scenario of regular obstacles. The robot successfully navigated around obstacles in accordance with the specified rules, following a predetermined path. The improved algorithm consistently updates the path in real-time at each time step, ensuring effective navigation by the robot while adhering to the established rules.

In summary, the improved algorithm performs admirably in various scenarios, effectively addressing situations involving complex shapes, a large number of obstacles, and rule-based constraints. The real-time updating of the path planning allows the robot to adapt flexibly to different environments, ensuring both the accuracy and timeliness of navigation. These results indicate that the embedded navigation system, coupled with the fuzzy control’s P/N local path planning algorithm, exhibits excellent adaptability and performance in complex environments.

3.4 Discussion

Unlike the navigation system in this research, Lagunes et al. (2021) proposed a competitive multiple heuristic optimization model for the parameter optimization design of fuzzy system member functions. The fuzzy system controls the navigation of the autonomous mobile robot along the desired trajectory. The model comprises a firefly algorithm, wind-driven optimization, uncrewed aerial vehicle (UAV) squadron optimization, and random fractal search. Its main contribution is to use four meta-heuristic methods working competitively to find the best vector of data generated with the optimal value and adjust the membership function of the fuzzy controller [18]. Jeong and Park (2021) proposed a fuzzy logic system to solve the problem that the Global Position System (GPS) cannot determine the position of vehicles in the shadow area.

This system analyzes the chromaticity and frequency component ratio of light-emitting diode (LED) lights installed under the ceiling to determine
the position of mobile robots in the GPS shadow room environment. The results show that this method is suitable for applying automatic vehicle navigation in areas with poor signal reception [19]. Sahloul et al. (2021) studied the navigation of autonomous nonholonomic mobile robots in some known environments. In the online phase of the navigation process, the mobile robot uses a sliding mode controller to follow the planned trajectory, which can avoid unexpected obstacles by using a fuzzy logic controller. The simulation results show that the proposed path planning method is simple and effective and prove that the sliding mode controller tracks the reference trajectory more accurately than the fuzzy logic controller [20]. The research results show that the core advantage of the navigation system is its improved FCA, especially the effectiveness of introducing the normal weight flag bit into the system. The robot has a good obstacle avoidance trajectory and better straight-line motion performance and finally can realize the adverse impact of angular velocity setting on the performance of the robot path algorithm.

4. Conclusions

The research content is the mechatronic robot navigation system, mainly including local path planning and autonomous obstacle avoidance technology. Traditional ultrasonic sensors have the problems of large blind areas and unreasonable detection range in the presence of obstacles. The new ultrasonic sensor array is optimized to achieve the detection result that the robot has a very small blind area. Additionally, a new P/N local path planning algorithm with improved fuzzy control is proposed. Based on type simulation experiments, some conclusions are drawn. 1. The new local path algorithm has better anti-shock ability and running performance, making the robot's running trajectory smoother and shorter. 2. The proposed new local path planning can achieve reasonable path planning in the simulation of real-life scene 3. The simulation experiment of the combined Simulink and ROS system shows that the local path planning algorithm can achieve a relatively ideal navigation situation. However, some shortcomings remain. For example, when the surface roughness of the obstacle or the angle between the ultrasonic beam and the obstacle is too large, the range of the ultrasonic sensor may be inaccurate. The parameter adjustment of the membership degree of fuzzy rules is not convenient enough. Future work needs to add other sensors for fusion obstacle avoidance detection and study the fuzzy control characteristics to improve the algorithm's applicability. This research hopes to provide more suitable theoretical and technical references for optimizing the mechatronic robot navigation system through efforts.

Acknowledgement

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