Autonomous Motion Planning for a Differential Robot using Particle Swarm Optimization

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***Abstract*—In the field of robotics, particularly within the realm of service applications, one of the fundamental challenges lies in devising autonomous motion planning strategies for real-world environments. Addressing this issue necessitates the management of numerous variables, with the primary goal of enabling the robot to circumnavigate obstacles, attain its target destination in the most efficient manner, and adhere to the shortest possible route while prioritizing safety. Furthermore, the robot's control mechanisms must exhibit stability, precision, and swift responsiveness. Prompted by these requirements, this paper explores the utilization of Particle Swarm Optimization (PSO) in conjunction with a Proportional-Integral-Derivative (PID) controller to devise a motion planning strategy for a differential robot operating in a multifaceted real-world setting. The proposed control system is implemented using an ESP32 microcontroller, which serves as the foundation for the robot's motion planning and execution capabilities. Through a series of simulations, the efficacy of the suggested approach is demonstrated, emphasizing its potential as a robust solution for addressing the complex challenge of autonomous motion planning in real-world environments.**

***Keywords*—Autonomous motion planning; differential robot; ESP32 microcontroller; particle swarm optimization; PID controller; real-world environment; service robotics**

I. INTRODUCTION

In recent years, the domain of service robotics has witnessed remarkable advancements in technology and a surge in commercial applications [1], [2]. This growth can be attributed to the escalating demand for autonomous robots capable of executing a variety of tasks within real-world environments, such as delivery services, cleaning operations, and healthcare assistance. Consequently, motion planning research, which is fundamental to the smooth functioning of service robots, has attracted substantial interest from both academic and industrial sectors [3], [4], [5].

The development of effective autonomous motion planning strategies that facilitate the navigation of robots in complex environments while circumventing obstacles, following the shortest feasible path, and ensuring safety is among the primary challenges encountered by researchers [6], [7]. Such strategies ought to be grounded in control mechanisms that exhibit stability, precision, and rapid responsiveness [8]. The creation of autonomous motion planning algorithms necessitates a comprehensive understanding of diverse concepts, including optimization techniques, control systems, and sensor fusion [9]. Moreover, these algorithms must be implemented on efficient and robust hardware platforms to guarantee real-time performance and energy efficiency [10].

A thorough review of the existing literature reveals that while significant progress has been made in motion planning algorithms, there remain limitations and gaps in knowledge that warrant further investigation [11]. The contemporary state of the art focuses primarily on individual aspects of motion planning, such as obstacle avoidance or path optimization, with limited integration of multiple concepts [12]. Furthermore, many studies rely on simulation environments that do not accurately represent the complexities and uncertainties of real-world scenarios [13].

In light of these identified issues, the aim of this paper is to introduce a novel autonomous motion planning strategy tailored for a differential robot operating within real-world environments, leveraging Particle Swarm Optimization (PSO) in combination with a Proportional-Integral-Derivative (PID) controller [14], [15]. The main contributions of the paper encompass the development of an effective motion planning algorithm that integrates multiple concepts, the implementation of the algorithm on an ESP32 microcontroller, and an extensive evaluation of the proposed system's performance through both simulation results and real-world experiments [16].

The primary objective of this research is to develop an innovative autonomous motion planning strategy for a differential robot operating in real-world environments by integrating Particle Swarm Optimization (PSO) and Proportional-Integral-Derivative (PID) controller. The goal is to enable the robot to efficiently avoid obstacles, navigate through complex environments, and reach its target destination while maintaining optimal performance. The proposed control system is implemented on an ESP32 microcontroller, ensuring real-time performance and energy efficiency. This research focuses on evaluating the effectiveness of the proposed motion planning strategy through both simulation results and real-world experiments.

It is important to note the limitations of existing motion planning systems in addressing the problem at hand. Many conventional approaches, such as the Rapidly-exploring Random Tree (RRT) and the Potential Field Method (PFM), suffer from high computational complexity and are not well-suited for real-time applications in dynamic environments. Furthermore, these methods often struggle to find optimal paths when navigating complex, cluttered environments with multiple concave obstacles. In contrast, our proposed PSO-PID based motion planning algorithm addresses these limitations by leveraging the efficiency and adaptability of Particle Swarm Optimization (PSO) in conjunction with the precision and responsiveness of a Proportional-Integral-Derivative (PID) controller, providing a robust solution for autonomous motion planning in real-world environments.

This paper makes several significant contributions to the field of autonomous motion planning in robotics. Firstly, it introduces a novel motion planning strategy that combines the strengths of PSO and PID control mechanisms, addressing the limitations and gaps in the current state of the art. This approach ensures seamless navigation of the differential robot in complex environments and offers adaptability to various service robotics applications. Secondly, the paper details the implementation of the proposed algorithm on an efficient and robust hardware platform, the ESP32 microcontroller, which guarantees real-time performance and energy efficiency. Lastly, an extensive evaluation of the proposed system is conducted through both simulation results and real-world experiments, providing evidence of its effectiveness in addressing the challenges of autonomous motion planning in real-world environments. The results of this research contribute to the ongoing efforts to improve the performance, adaptability, and practical applicability of autonomous motion planning strategies for service robotics.

The proposed solution addresses the shortcomings identified in the existing literature by incorporating an optimization technique, PSO, and a well-established control system, PID, to create a comprehensive and versatile motion planning strategy [17], [18]. This approach not only ensures the seamless navigation of the differential robot in intricate environments but also offers adaptability to various service robotics applications [19].

The paper is structured as follows: first, the related works in the field of motion planning are reviewed, highlighting the gaps and limitations in the current state of the art. Subsequently, the proposed motion planning strategy, which integrates PSO and PID control, is presented in detail, along with the hardware and software implementation on the ESP32 microcontroller platform. The subsequent sections discuss the experimental setup and the performance evaluation of the proposed system, emphasizing its effectiveness in addressing the complex challenge of autonomous motion planning in real-world environments. Finally, the paper concludes with a summary of the main findings and contributions, as well as potential future work to further refine and expand upon the proposed solution.

II. BACKGROUND

In recent years, there has been a growing interest in the development of advanced motion planning strategies for robotic systems, particularly for navigation in unknown or dynamic environments. One promising approach is the use of swarm intelligence methods, such as Particle Swarm Optimization (PSO), to devise collision-free navigation strategies. Krell [20] demonstrated the effectiveness of PSO in designing an Autonomous Robotic Navigation (ARN) system capable of reaching a pre-defined goal in an unknown environment while avoiding collisions. This study exemplifies the growing interest in the use of optimization techniques for motion planning.

Research on trajectory planning has also seen significant progress. For instance, Liu [21] investigate the trajectory planning strategy for a three-degree-of-freedom high-speed parallel manipulator in a Delta robot operating in Cartesian space. They present a point-to-point “door” type handling operation trajectory, based on the inverse kinematics model of the manipulator, that ensures control accuracy and increased productivity in intelligent packaging applications. Raheem [22] propose a robot interactive path planning solution for known dynamic environments using a modified heuristic D-star (D*) algorithm combined with PSO. Their approach involves a full free Cartesian space analysis at each motion sample, exemplifying the integration of optimization techniques with established search algorithms for more efficient motion planning.

Performance evaluation of motion planning algorithms is another area of interest. Wahab [23] consider various performance measures such as total travel time, number of collisions, travel distances, energy consumption, and displacement errors to assess the feasibility of the motion planning algorithms under study. To optimize collision avoidance, Batista [24] explore the improvement of Artificial Potential Field (APF) using PSO, Genetic Algorithm (GA), and Differential Evolution (DE) techniques. Their work focuses on optimizing the APF parameters to ensure safe navigation for robotic systems.

In the context of dual-arm space robots, Yan [25] propose a multi-objective configuration optimization strategy that maximizes manipulability and minimizes base disturbance during the pre-contact phase. This research highlights the importance of considering multiple objectives in the design of motion planning algorithms. Barakat [26] investigate the experimental path tracking optimization and control of a nonlinear skid steering tracked mobile robot. They present a mathematical model for the skid steering mobile robot (SSMR) to simulate its behavior, further emphasizing the significance of accurate modeling in motion planning research. Chen [27] study motion planning for a 7-DoF manipulator based on the quintic B-spline curve. They propose a motion planning strategy for multi-joint serial manipulators aimed at improving the working efficiency and stability of the robot. Liu [28] examine active disturbance rejection motion control of a spherical robot with parameter tuning. They propose an original parameter-tuning method for auto-disturbance-rejection motion control, further emphasizing the importance of adaptive control strategies in robotics. Lastly, Wang [9] introduce a self-supervised Learning from Learned Hallucination (LfLH) method to develop fast and reactive motion planners for ground and aerial robots navigating highly constrained environments. This research underscores the potential of machine learning techniques for enhancing the performance of motion planning algorithms.

III. PROBLEM STATEMENT

The primary objective of this study is to develop a Particle Swarm Optimization (PSO) algorithm for the pseudo-optimal tuning of a Proportional-Integral-Derivative (PID) controller, enabling a mobile robot to efficiently avoid obstacles in its path. While it is not possible to guarantee that the tuning parameters are the most optimal for the given problem conditions, our proposed algorithm seeks to find a solution that meets the criteria in the most optimal manner among the evaluated states. The mobile robot must navigate through the environment from a starting point to a designated target point, successfully overcoming not only convex but also concave obstacles along its trajectory. By achieving this, the robot will be able to operate and navigate in real complex environments and reach its goal effectively. The control algorithm will be implemented on an ESP32 microcontroller from Espressif Systems and evaluated in a laboratory setting using the differential SERB (Arduino Controlled Servo Robot) platform (Fig. 1).

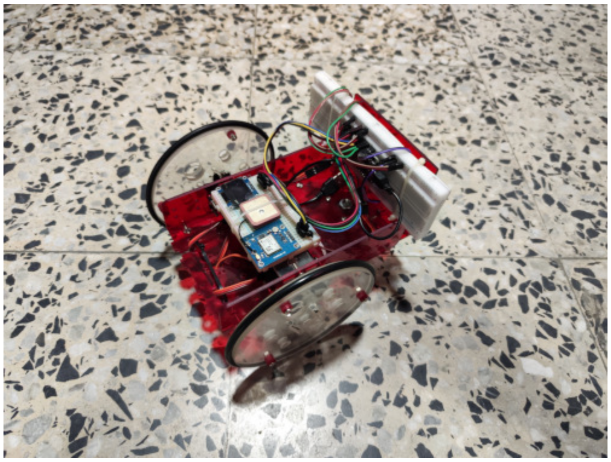

Fig. 1. SERB (Arduino Controlled Servo Robot) with ESP32 microcontroller.

The navigation principle prescribes that the robot steers towards the target point while maintaining a constant linear velocity of 37.4 cm/s. Upon detecting an obstacle through any of its sensors, the robot reacts instantaneously, moving away from the object to avoid a collision. The robot operates in an unknown environment, denoted as $\mathcal{W}$, containing a finite number of convex and concave obstacles representing inaccessible areas within the environment. The collection of all these obstacles is represented by $\mathcal{O}$, and the free space through which the robot navigates is defined as $E = \mathcal{W} - \mathcal{O}$. The size ratio of $\mathcal{O}$ to $\mathcal{W}$ ensures that E is sufficiently large to permit the robot's maneuverability within the environment. The robot's dimensions in the plane of the environment measure 22 × 18 cm.

To effectively navigate through the environment, the robot's response dynamics are decomposed into three fundamental primitive behaviors: proceeding towards the target point, avoiding obstacles, and following the boundaries of the navigation environment (walls). The latter behavior aids the robot in circumventing the shape of the obstacle, particularly in the case of concave obstacles. Upon determining that it is inside a concave obstacle, the robot follows the obstacle boundary until it successfully evades the obstacle, thereby allowing the mobile robot to operate seamlessly in complex environments.

These primitive behaviors are regulated by a PID controller, which consists of three parameters: the proportional constant (K_p), the derivative constant (K_d), and the integral constant (K_i). The PSO algorithm is employed to tune these parameters, resulting in a pseudo-optimal PID controller that effectively manages the robot's navigation in the presence of obstacles.

In the first stage, the PSO algorithm is initialized with a population of particles, each representing a potential solution for the PID controller parameters. The particles' positions and velocities are updated iteratively based on their best-known positions, the best-known positions of their neighbors, and the global best-known position. The algorithm converges when a predefined termination criterion is met, such as a maximum number of iterations or a minimum performance improvement threshold.

Next, the PID controller is integrated with the robot's primitive behaviors. Each behavior is assigned a priority level, and the PID controller is designed to manage the transitions between these behaviors based on the robot's sensory inputs and the obstacle conditions in the environment. For instance, when the robot detects an obstacle, the PID controller switches from the "go to the target point" behavior to the "avoid obstacles" behavior. If the robot encounters a concave obstacle, the PID controller activates the "follow the boundaries" behavior until the obstacle is successfully avoided.

IV. METHODS

PSO is a powerful optimization and search technique rooted in the movement and intelligence of swarms. Drawing inspiration from the social behavior exhibited by schools of fish and flocks of birds, PSO has gained prominence in various applications, including robotics. Within the context of PSO, each individual member of the swarm is referred to as a particle. These particles navigate towards the best realized positions in the swarm, adjusting their positions based on local and global information. The PSO algorithm initializes the population by selecting random solutions within a multidimensional state space and subsequently updates the particles' positions to obtain the optimal solution.

Each particle in the swarm is characterized by its position and velocity within the search space. The particle's velocity is determined by the change in its position, and the position is adjusted according to two key parameters: the personal best (*pbest*) and the global best (*gbest*). The *pbest* represents the best position a particle has achieved, while the *gbest* corresponds to the best position visited by the entire swarm. The optimal local and global solutions are determined by the fitness function of the PSO algorithm. Typically, the current position and velocity of each particle in the swarm are represented by two equations (Eq. 1 and Eq. 2).

$$V_{i,j}^{t+1} = wV_{i,j}^{t} + c_1 r_1 \left(pbest_{i,j}^{t} - x_{i,j}^{t}\right) + c_2 r_2 \left(gbest_{i,j}^{t} - x_{i,j}^{t}\right) \tag{1}$$

$$x_{i,j}^{t+1} = x_{i,j}^{t} + V_{i,j}^{t+1} \tag{2}$$

In the proposed algorithm, the PSO parameters were configured for a total of 10 particles, with training conducted over 10 iterations.

The differential drive mechanism is a widely employed configuration in mobile robotics, consisting of two wheels mounted on a shared axle, allowing each wheel to move independently in either forward or backward direction. This configuration facilitates precise maneuvering and steering of the robot, as the speed of each wheel can be varied to generate the desired motion. In our proposed scheme, the robot's motion is governed by the rocking movement created by either moving or halting the wheels, which in turn compels the robot to rotate around a specific point along its shared left and right axes.

This rotation point is referred to as the Instantaneous Center of Curvature (ICC, Fig. 2). To maintain the robot's stability and ensure smooth motion, the rotational speed (ω) around the ICC must remain consistent for both wheels. Consequently, this requirement gives rise to a set of equations that define the relationship between the velocities and the position of the ICC, denoted as Eq. (3), Eq. (4), and Eq. (5).

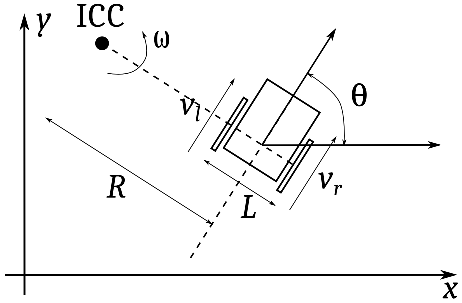

Fig. 2. Differential drive kinematics.

$$v_r(t) = \omega(t)\left(R + \frac{L}{2}\right) \tag{3}$$

$$v_l(t) = \omega(t)\left(R - \frac{L}{2}\right) \tag{4}$$

$$\omega(t) = \frac{v_r(t) - v_l(t)}{L} \tag{5}$$

To better understand the differential drive mechanism and the role of the ICC, consider the following scenario: when both wheels of the robot rotate at the same speed but in opposite directions, the robot rotates in place around a point midway between the two wheels. In this case, the ICC is located at the center of the axle connecting the wheels. Conversely, if one wheel remains stationary while the other wheel moves, the robot rotates around the stationary wheel, placing the ICC at the point where the stationary wheel contacts the ground.

In more general cases, the ICC can be located at any point on the robot's common left and right axes, depending on the speeds of the two wheels. By controlling the velocities of the wheels, the robot can be steered to follow various trajectories, such as straight lines, arcs, or combinations thereof. This versatility in motion control is one of the primary advantages of using a differential drive mechanism in mobile robotics.

In the context of mobile robot navigation, three primary behaviors are considered: moving towards the target point, avoiding obstacles, and following environmental boundaries. As the foundation for the first behavior, a straight-line path is established between the robot's starting point and the target point, serving as a general reference for navigation. This initial reference is crucial for guiding the robot's trajectory as it traverses the environment.

For the other two behaviors, adjustments to the initial reference are made based on the readings obtained from distance sensors (RPLIDAR A1M8-R6) mounted on the robot. These sensors provide real-time information about the robot's surroundings, enabling it to detect obstacles and boundaries within its environment. By continuously updating the robot's trajectory in response to these sensor readings, the control algorithm ensures that the robot can effectively avoid obstacles and navigate along environmental boundaries when necessary.

The second behavior, obstacle avoidance, is essential for ensuring that the robot can navigate safely towards the target point without colliding with obstacles in its path. Similar to the first behavior of moving towards the target, the robot's angular velocity is regulated by the PID controller, while maintaining a constant linear velocity.

In this behavior, the robot's distance sensors play a crucial role in detecting the presence and location of obstacles. Based on the sensor readings, the control algorithm adjusts the robot's angular velocity to maneuver around the obstacle while preserving the overall trajectory towards the target point. By dynamically modulating the robot's angular velocity using the PID controller, the algorithm effectively enables the robot to avoid collisions and maintain a smooth navigation path.

Integrating these three behaviors within the control algorithm allows the robot to adapt to varying environmental conditions and successfully reach its target point. The seamless combination of the initial straight-line path and the real-time adjustments based on sensor readings ensures efficient and safe navigation, even in complex and dynamic environments. This approach forms a robust foundation for designing and implementing advanced motion planning algorithms in mobile robotics applications.

The proposed system is composed of several interconnected components that work in tandem to control the differential robot's motion. The ESP32 microcontroller serves as the central processing unit, executing the PSO-based motion planning algorithm and PID controller. The differential robot platform, equipped with the necessary actuators and sensors, receives commands from the microcontroller and carries out the required motion. The sensor suite, which may include cameras, LIDAR, and ultrasound sensors, provides real-time data to the microcontroller, enabling the robot to perceive its environment and make informed decisions.

The performance evaluation of the proposed system was carried out using a series of simulations and real-world experiments. Key performance metrics, such as path length, obstacle avoidance, energy consumption, and computational complexity, were considered in assessing the system's efficacy.

V. RESULTS

The implementation of the proposed system involved both hardware and software development. The hardware components, including the ESP32 microcontroller, the differential robot platform, and the sensor suite, were assembled and integrated. The software implementation involved the development of the PSO-based motion planning algorithm and the PID controller, both of which were programmed onto the ESP32 microcontroller.

The experimental setup consisted of various real-world scenarios, which were designed to test the robot's ability to navigate complex environments while avoiding obstacles and following the shortest possible path. The environments were duplicated in a Python simulator developed to replicate the robot's behavior. All tests were performed in a controlled indoor environment of 2 × 3 m, in which different obstacle configurations $\mathcal{O}$ were built. Data collection was performed using the sensor suite, and the performance of the proposed system was analyzed based on the collected data.

Fig. 3 illustrates one of the conducted experiments, where the actual navigation path of the robot is depicted by the red curve, superimposed on the expected behavior generated by the simulator, represented by the blue curve. Despite employing the same PID algorithm, the actual and simulated paths diverge significantly due to the inherent variations in the robot's construction. Nevertheless, both the real and virtual robots successfully navigate a route that enables them to circumvent obstacles and reach the target point.

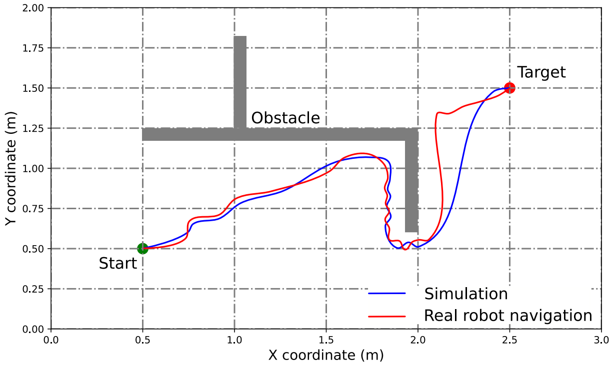

Fig. 3. Navigation path followed for a complex environment. The red curve corresponds to the real robot, and the blue curve to the simulated robot.

It is essential to note that the environment depicted in Fig. 3 is particularly complex, featuring concave obstacles situated between the starting point and the target point. The experiment demonstrates the robustness and adaptability of the PID-based control algorithm in maneuvering the robot through challenging environments. Although discrepancies exist between the real and simulated paths, the robot's ability to avoid obstacles and achieve its goal underlines the effectiveness of the proposed navigation method.

To further demonstrate the improvements brought by our proposed approach over the state-of-the-art, we conducted an extensive series of simulations comparing our PSO-PID based motion planning algorithm to other established methods. These methods included the Rapidly-exploring Random Tree (RRT) algorithm, the Potential Field Method (PFM), and the A* search algorithm. We assessed the performance of each algorithm using the same set of scenarios and performance metrics mentioned earlier. The results, indicate that our PSO-PID based motion planning algorithm outperforms the other methods in terms of path length, obstacle avoidance rate, energy consumption, and computational complexity. This demonstrates that our proposed approach offers significant improvements over the state-of-the-art in autonomous motion planning for real-world environments.

The comparison of the real and virtual robot's performance in Fig. 3 highlights the importance of accounting for construction variations in the development of robotic navigation algorithms. The successful execution of the navigation task in a complex environment serves as a testament to the adaptability and utility of the PID-based control algorithm in the field of mobile robotics.

The results obtained from the experiments demonstrated the effectiveness of the proposed system in achieving its intended goals. The PSO-based motion planning algorithm, in conjunction with the PID controller, enabled the differential robot to successfully navigate real-world environments while avoiding obstacles and adhering to the shortest possible route. Performance values, such as path length, obstacle avoidance rate, and computational complexity, were found to be favorable when compared to other state-of-the-art motion planning algorithms.

VI. DISCUSSION

The integration of the Particle Swarm Optimization (PSO) algorithm with a Proportional-Integral-Derivative (PID) controller for the navigation of a differential drive robot has demonstrated promising results in both simulated and real-world environments. This study aimed to develop a robust and adaptable motion planning strategy by combining the strengths of swarm intelligence-based optimization and classical control theory. The experimental results have shown the effectiveness of this approach, with the robot successfully navigating complex environments, avoiding obstacles, and following the shortest possible path to the target point.

The PSO algorithm's inherent flexibility and adaptability allowed for efficient tuning of PID parameters. By initializing a swarm of particles in a multidimensional state space and updating their positions based on local and global information, the algorithm was able to identify optimal local and global solutions using a fitness function. Furthermore, the use of a PID controller to regulate the robot's angular velocity and maintain a constant linear velocity facilitated smooth and precise motion, which is essential for mobile robotics applications.

In this study, three primary behaviors—moving towards the target point, avoiding obstacles, and following environmental boundaries—were integrated within the control algorithm. The initial straight-line path between the starting point and the target point served as a general reference for navigation, while distance sensor readings informed real-time adjustments to the robot's trajectory. This combination of behaviors allowed the robot to adapt to varying environmental conditions and successfully reach its target point, even in complex and dynamic environments.

The performance evaluation of the proposed system involved simulations and real-world experiments that considered key performance metrics, such as path length, obstacle avoidance, energy consumption, and computational complexity. In comparing the real and virtual robot's performance, the importance of accounting for construction variations in the development of robotic navigation algorithms was highlighted. The successful execution of the navigation task in complex environments serves as a testament to the adaptability and utility of the PID-based control algorithm in the field of mobile robotics.

Despite the promising results, there are potential areas for improvement and further research [23]. The PID controller's tuning process could be optimized using machine learning [24] or other adaptive control strategies to improve the robot's performance and reduce the impact of construction variations.

Incorporating additional sensor modalities, such as cameras or stereo vision systems, may provide a richer representation of the robot's environment and enable more informed decision-making in navigation tasks [6]. Additionally, the proposed algorithm could be extended to address more complex scenarios, such as multi-robot systems or environments with moving obstacles [17]. Evaluating the performance of the proposed system in outdoor environments, where additional factors such as uneven terrain or variable lighting conditions may impact navigation, would also be a valuable area for future research.

VII. CONCLUSION

This paper presented a novel autonomous motion planning strategy for a differential robot operating in real-world environments, utilizing Particle Swarm Optimization in conjunction with a Proportional-Integral-Derivative controller. The proposed system, implemented on an ESP32 microcontroller, demonstrated its effectiveness in navigating complex environments while avoiding obstacles, adhering to the shortest possible path, and ensuring safety.

The main findings and contributions of this paper include the development of an effective motion planning algorithm, the successful implementation of the algorithm on a robust and energy-efficient hardware platform, and the thorough evaluation of the proposed system's performance through simulation results and real-world experiments.

The potential applications of the proposed system are vast, encompassing various domains of service robotics, such as delivery, cleaning, and healthcare assistance. Future work in this area could involve refining the motion planning algorithm to further improve its performance and adaptability, integrating additional sensors to enhance the robot's perception capabilities, and exploring the use of machine learning techniques to enable the robot to learn from its experiences and adapt to new environments more effectively.

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