



An Experiential Learning Framework for Mobile Robot Control Using PID-Based Path Tracking

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ABSTRACT– Mobile robot path tracking is a fundamental problem in control systems and robotics and has been widely utilized as a platform for integrating multidisciplinary concepts in mechatronics education. This study proposes an experiential learning framework for mobile robot control using a PID-based path tracking approach. The framework integrates theoretical control principles with hands-on implementation through the development of a differential-drive mobile robot equipped with reflective sensor arrays and a microcontroller-based control unit. The PID controller is applied to regulate robot motion based on real-time feedback, and its parameters (K_p , K_i , K_d) are tuned experimentally using a structured trial-and-error procedure. Experimental results indicate that the PID controller improves tracking stability and reduces oscillatory behavior compared to proportional-only control. The optimal parameter configuration ($K_p=0.8$, $K_d=0.32$, $K_i=0.2$) achieves stable tracking performance across different trajectory conditions, including curved paths. From an educational perspective, the proposed framework supports experiential and project-based learning by enabling systematic analysis of control system behavior through iterative experimentation. This work provides a practical and scalable approach for integrating control theory and robotic implementation in mechatronics education.

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Introduction

Mobile robots have become an essential platform in modern mechatronics systems, with applications in industrial automation, autonomous navigation, and intelligent transportation. One of the most critical capabilities of mobile robots is path tracking, which ensures that the robot can follow a predefined trajectory accurately under dynamic conditions. This problem has been widely studied due to its practical importance, particularly in environments affected by disturbances, nonlinear dynamics, and sensor uncertainties [1], [2]. Among various control strategies, proportional–integral–derivative (PID) control remains one of the most widely used approaches due to its simplicity, robustness, and ease of implementation in embedded systems [3], [4].

PID control has been successfully applied in different types of mobile robots, including differential-drive and omnidirectional systems. Several studies have demonstrated that properly tuned PID controllers can achieve stable and accurate trajectory tracking [5], [6]. In addition, advanced variations such as adaptive PID, fuzzy-PID, and hybrid control methods have been proposed to improve system robustness and tracking performance in complex environments [7], [8]. Despite these developments, classical PID control remains highly relevant due to its low

computational requirements and suitability for real-time applications [9], [10].

Beyond engineering applications, mobile robot platforms—particularly line-following robots—have been widely utilized as educational tools in robotics and mechatronics learning environments. These systems provide an accessible platform for integrating multidisciplinary concepts such as control theory, embedded programming, sensor systems, and mechanical design [11], [12]. Through hands-on experimentation, students can observe fundamental control phenomena including error dynamics, feedback response, oscillatory behavior, and steady-state error. The trial-and-error tuning of PID parameters (K_p , K_i , K_d) also provides a practical learning experience that connects theoretical knowledge with real-world implementation [13], [14].

Recent studies have highlighted the importance of experiential and project-based learning approaches in engineering education, particularly in robotics. These approaches enhance students' problem-solving abilities, critical thinking, and system integration skills by engaging them in real-world engineering challenges [12], [15]. However, despite the growing use of mobile robots in education, there is still a lack of structured frameworks that

systematically integrate control theory with hands-on implementation. Most existing works focus either on improving control performance or on developing educational tools independently, without providing a comprehensive learning model that connects theory, experimentation, and iterative learning processes.

Therefore, this study proposes an experiential learning framework for mobile robot control using PID-based path tracking. The proposed framework integrates theoretical PID control concepts with practical implementation using a differential-drive mobile robot platform. It emphasizes iterative experimentation, parameter tuning, and system analysis to enhance both conceptual understanding and practical skills. The main contribution of this work is to provide a structured, experiment-driven learning approach that bridges the gap between control theory and real-world robotic implementation in mechatronics education.

Material and Methods

This study adopts an experiential learning approach by integrating theoretical control concepts with practical implementation using a PID-controlled mobile robot platform. The methodology is structured into four main stages: system design, hardware development, control algorithm implementation, and experimental validation. This structured approach enables systematic analysis of the relationship between control theory and real-world robotic systems through iterative experimentation.

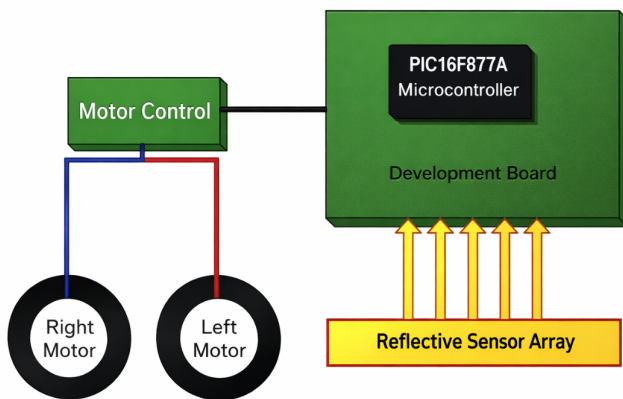


Figure 1. Block Diagram of the Mobile Robot System Architecture

The overall architecture of the mobile robot system is illustrated in Figure 1, which shows the integration of sensing, control, and actuation subsystems. The robot employs a differential drive mechanism controlled by a microcontroller unit (MCU). Sensor data obtained from the reflective sensor array are processed to generate control signals for motor actuation. The system operates in a closed-loop configuration, where feedback continuously updates the control input, enabling real-time path tracking.

The mechanical structure of the mobile robot, as shown in Figure 2, consists of a lightweight chassis, two driven wheels, and passive caster supports to maintain stability. The selection of wheel radius and motor characteristics influences both velocity and torque, which directly affect tracking

performance. This configuration allows analysis of the trade-off between speed and stability in mobile robot operation.

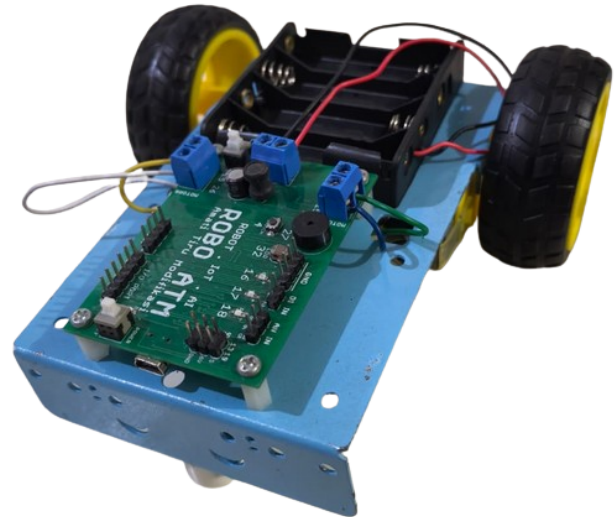


Figure 2. Mechanical Design of the Mobile Robot Platform

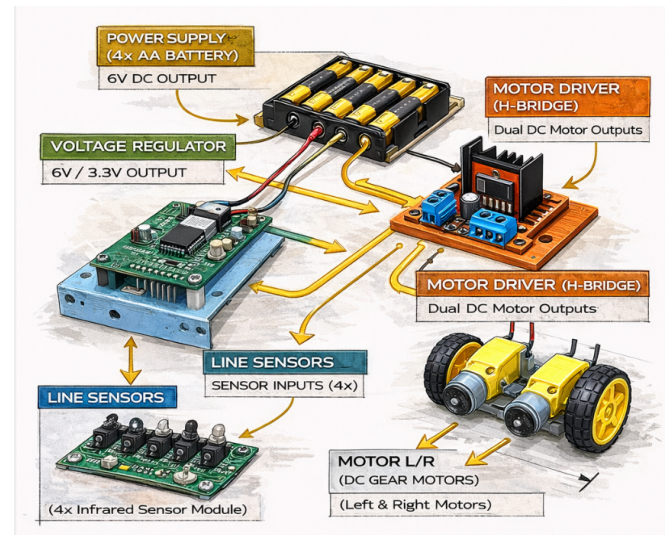


Figure 3. Electronic System Integration of Microcontroller, Sensors, and Motor Drive

The electronic system architecture, presented in Figure 3, integrates the microcontroller, sensor array, motor driver, and power supply. A PIC16F877A microcontroller is used as the central processing unit due to its suitability for embedded control applications. The reflective sensor array detects the line position and produces signals corresponding to the robot's relative position. These signals are converted into error values, which are used as inputs to the control algorithm.

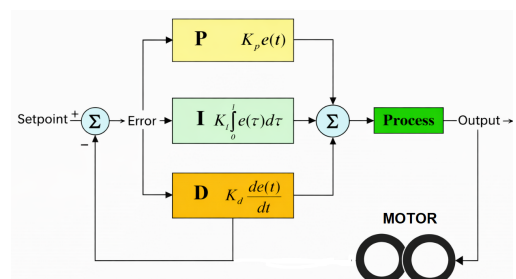


Figure 4. Block Diagram of PID Control System for Mobile Robot

The control strategy implemented in this study is based on the classical PID controller, as illustrated in Figure 4. The controller computes the control signal based on the error between the desired position (set point) and the measured position obtained from the sensors. The PID control law is expressed as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

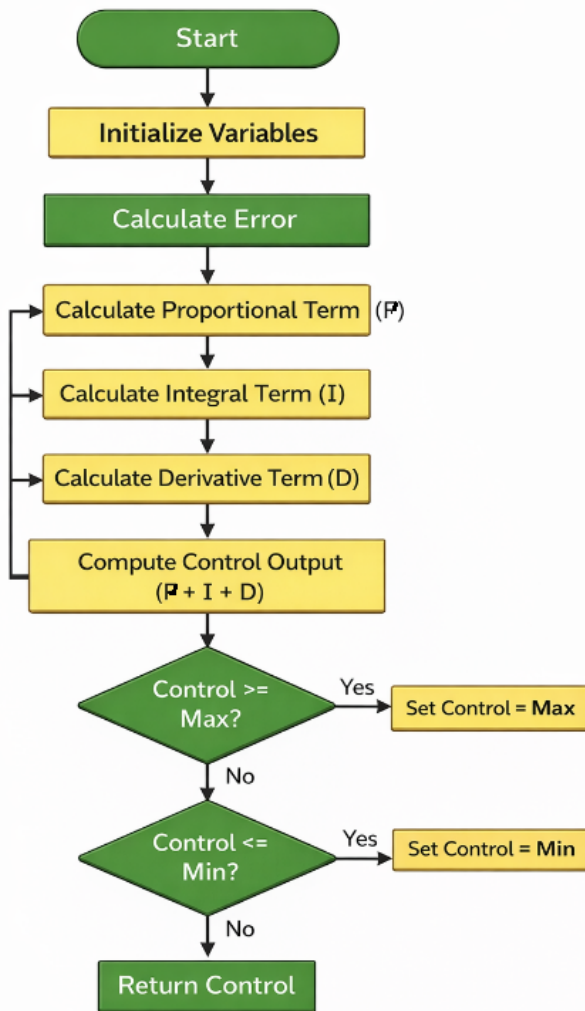


Figure 5. Implementation of PID Algorithm in Embedded System

Where $u(t)$ is the control signal, $e(t)$ is the tracking error, and K_p , and K_d are the proportional, integral, and derivative gains, respectively. The proportional term responds to the current error, the integral term accumulates past errors to eliminate steady-state deviation, and the derivative term predicts future error trends to improve system stability.

To support practical implementation, the PID algorithm is embedded in the microcontroller program, as shown in Figure 5. The algorithm processes sensor inputs in real time and generates control signals that regulate motor speed through pulse-width modulation (PWM). The tuning of PID parameters is conducted experimentally using a systematic trial-and-error procedure. The tuning process begins with adjusting the proportional gain to achieve basic responsiveness, followed by the derivative gain to reduce oscillations, and finally the integral gain to minimize steady-state error.

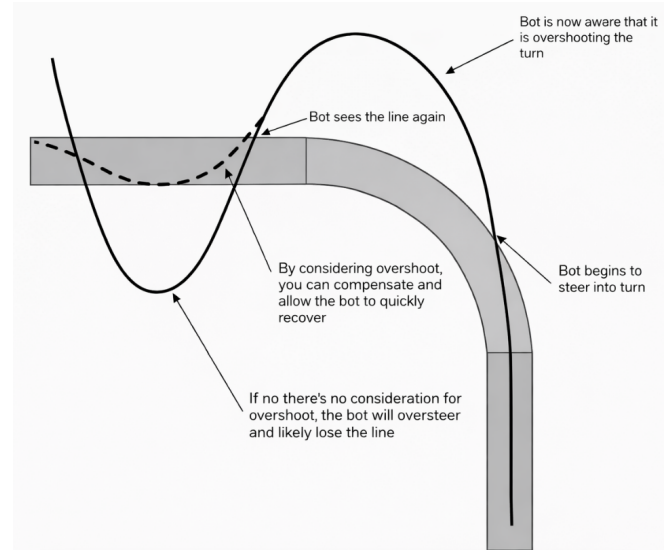


Figure 6. Experimental Setup of Line Following Path Tracking

The experimental setup for path tracking is illustrated in Figure 6, where the robot follows a predefined trajectory consisting of straight paths and curved sections. The experiments are conducted under controlled conditions to evaluate system performance under different PID parameter configurations. This experimental procedure enables analysis of tracking accuracy, system stability, and the effect of parameter tuning on robot behavior.

Results and Discussion

The performance of the proposed PID-based mobile robot system was evaluated through a series of experimental tests focusing on path tracking accuracy and system stability. The experiments were conducted using a predefined trajectory consisting of straight paths and curved sections (90° and 135° turns), allowing comprehensive analysis of the robot's dynamic behavior under varying conditions..

The experimental results indicate that the proportional term (K_p) plays a dominant role in reducing the instantaneous tracking error. When only proportional control is applied, the robot is able to follow the path; however, it exhibits oscillatory behavior, particularly when navigating curved trajectories. This oscillation is caused by the lack of damping in the control system, which results in repeated overshoot around the desired path. This observation is consistent with classical control theory, where excessive reliance on proportional gain leads to instability..

The inclusion of the derivative term (K_d) significantly improves system stability by reducing oscillations and damping the robot's lateral motion. The derivative component enables the system to respond to the rate of change of error, allowing smoother transitions when the robot encounters curves. As a result, overshoot is reduced, and the tracking response becomes more stable, particularly in sharp turns such as 90° and 135° trajectories.

The integral term (K_i) contributes to eliminating steady-state error by accumulating past deviations. However, experimental observations show that excessive integral gain

introduces high oscillatory behavior due to overcompensation. This effect is particularly evident when the robot approaches the desired trajectory, where accumulated error causes the system to overshoot repeatedly. Therefore, appropriate tuning of the integral gain is required to balance steady-state accuracy and system stability.

From the experimental data, it is observed that configurations with high proportional and integral gains (e.g., $K_p=1$) result in unstable and highly oscillatory responses. In contrast, configurations with moderate proportional gain and properly tuned derivative and integral gains demonstrate improved stability. The optimal configuration is achieved at $K_p=0.8$, $K_d=0.32$, and $K_i=0.2$, where the robot exhibits stable tracking performance with minimal oscillation for both 90° and 135° curves. This indicates that balanced tuning of the three PID parameters is essential for achieving reliable path tracking.

Furthermore, the use of an 4-sensor array enhances the resolution of line detection, allowing more accurate estimation of the robot's position relative to the path. The sensor data are processed into a continuous error signal, which enables finer control of the robot's motion. This contributes to improved responsiveness and reduces the likelihood of losing the tracking line, especially during high-speed operation and sharp turns.

From an educational perspective, the experimental results demonstrate the effectiveness of the proposed experiential learning framework. The iterative tuning process allows learners to analyze the relationship between control parameters and system behavior, including oscillation, overshoot, and stability. This approach supports the development of analytical thinking and problem-solving skills, as learners must evaluate system responses and adjust parameters accordingly.

Overall, the results show that the proposed PID-based control system achieves reliable path tracking performance while simultaneously serving as an effective educational platform. The integration of control theory, embedded systems, and experimental validation provides a comprehensive learning experience that bridges theoretical knowledge and practical implementation in mechatronics education.

Table 1. Experimental result

RUN	K_p	K_d	K_i	CURVE 90°	CURVE 135°
1	1	0	0	moderate stability	moderate stability
2	1	1	0	wobble	overshoot
3	1	1	1	Huge oscillatory behavior	oscillatory behavior
4	0.9	0.5	0.4	moderate stability	overshoot
5	0.9	0.375	0.4	overshoot	moderate stability
6	0.9	0.2	0.32	moderate stability	moderate stability
7	0.8	0.3	0.32	moderate stability	Not so stable
8	0.8	0.32	0.2	stable tracking performance	stable tracking performance

Conclusion

This study proposed an experiential learning framework for mobile robot control using a PID-based path tracking approach. The framework integrates theoretical control concepts with hands-on implementation using a differential-drive mobile robot, enabling a systematic understanding of mechatronics systems.

The experimental results demonstrate that the PID controller improves path tracking performance by reducing oscillations and enhancing system stability compared to proportional-only control. The proportional term provides immediate error correction, the derivative term improves damping and stability, and the integral term reduces steady-state error. The optimal parameter configuration ($K_p=0.8$, $K_d=0.32$, $K_i=0.2$) achieves stable tracking performance with minimal oscillatory behavior across different trajectory conditions.

From an educational perspective, the proposed framework supports experiential and project-based learning by enabling analysis of system behavior through iterative tuning and experimentation. This approach facilitates a deeper understanding of control systems and their practical implementation.

In conclusion, this work contributes to both control engineering and mechatronics education by providing a structured and practical framework that links control theory with real-world robotic systems. Future work may focus on incorporating advanced control strategies and developing quantitative evaluation methods to further enhance learning outcomes.

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