Adaptive Trajectory Control for Mobile Robots in Dynamic Environments

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Abstract
This paper presents an adaptive trajectory control system for mobile robots operating in dynamic and uncertain environments. The proposed method combines path planning with real-time trajectory adjustments based on sensor feedback, enabling robots to safely and efficiently navigate around moving obstacles. A layered control architecture is implemented using fuzzy logic and PID regulators to balance global trajectory adherence with local reactive behaviors. Simulation results demonstrate the system's ability to maintain stability and path accuracy under various disturbances and environment changes.

Keywords: adaptive control, mobile robot, trajectory tracking, dynamic environment, fuzzy-PID, obstacle avoidance, real-time navigation

INTRODUCTION

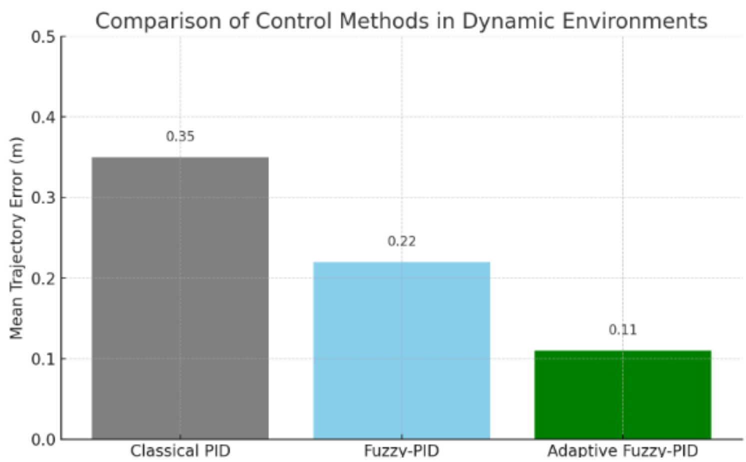
Autonomous mobile robots are increasingly deployed in dynamic environments such as warehouses, hospitals, and public spaces. These robots must follow predefined trajectories while reacting to unpredictable changes, including moving people, objects, or other robots. Traditional control systems often assume static surroundings and lack the flexibility to respond effectively to such changes.

To achieve robust mobility, adaptive trajectory control strategies are required. These systems dynamically adjust the robot's path or velocity profile in response to real-time sensory data. This paper explores the integration of adaptive control mechanisms into mobile robot navigation, focusing on how fuzzy-PID controllers can maintain trajectory fidelity while ensuring collision-free motion.

PROBLEM STATEMENT

Mobile robots operating in real-world environments face two major challenges: maintaining trajectory accuracy and avoiding dynamic obstacles. Classical trajectory tracking controllers often fail when unexpected objects appear in the path or when the surface or payload changes. This paper addresses the need for a control system that adapts its parameters on the fly, enabling the robot to continue its mission without manual intervention or recalibration.

METHODS



The proposed adaptive trajectory control system integrates both fuzzy logic and conventional PID control into a hybrid architecture. The base trajectory is generated using a global path planner, such as A* or RRT*, and is dynamically adjusted based on real-time obstacle detection using lidar or depth cameras.

The control algorithm utilizes a fuzzy-PID structure. Two inputs — position error and velocity error — are evaluated using fuzzy membership functions such as "Small", "Medium", and "Large". Based on these, control rules adjust the PID gains dynamically. This allows the controller to remain responsive to environmental changes without compromising trajectory tracking accuracy.

The algorithm was implemented in MATLAB/Simulink and tested in a simulated environment with moving obstacles and variable surface friction. Three control strategies — classical PID, fuzzy-PID, and adaptive fuzzy-PID — were evaluated. As shown in Fig. 1, the adaptive fuzzy-PID controller outperformed others in minimizing trajectory error in dynamic scenarios.

RESULTS

The performance of the proposed adaptive fuzzy-PID controller was evaluated in a simulated environment featuring dynamic obstacles and variable surface conditions. The primary performance metric was the mean trajectory error—the average distance between the robot's actual and desired paths during task execution.

Three control strategies were tested: classical PID, fuzzy-PID, and the proposed adaptive fuzzy-PID. As illustrated in Fig. 1, the classical PID controller exhibited the highest trajectory error (0.35 m), indicating limited adaptability in dynamic settings. The fuzzy-PID approach showed improvement (0.22 m), benefiting from rule-based reasoning. However, the adaptive fuzzy-PID controller achieved the best result (0.11 m), maintaining high accuracy even in unpredictable scenarios.

These results confirm that integrating adaptive fuzzy logic into the control loop significantly improves trajectory tracking in environments where traditional methods fail to compensate for external disturbances or system nonlinearities.

CONCLUSION

This study presented an adaptive fuzzy-PID control strategy for trajectory tracking in mobile robots operating within dynamic and uncertain environments. By combining the responsiveness of fuzzy logic with the stability of PID regulation, the proposed controller adapts in real time to changes such as moving obstacles and surface variability.

Simulation results demonstrated that the adaptive fuzzy-PID controller significantly reduced trajectory error compared to classical PID and standard fuzzy controllers. This improvement highlights the potential of adaptive control systems in enabling more robust and reliable robot navigation in real-world applications.

The proposed approach provides a scalable and flexible framework that can be extended to multi-robot coordination, real-world deployment, and integration with higher-level decision-making systems.

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АДАПТИВНЕ КЕРУВАННЯ ТРАЄКТОРІЄЮ МОБІЛЬНИХ РОБОТІВ У ДИНАМІЧНИХ СЕРЕДОВИЩАХ

Анотація

У статті представлено адаптивну систему керування траєкторією мобільних роботів, які функціонують у динамічному та невизначеному середовищі. Запропонований метод поєднує планування шляху з корекцією траєкторії в реальному часі на основі зворотного зв’язку із сенсорів, що дозволяє роботам безпечно та ефективно обходити рухомі перешкоди. Реалізовано багаторівневу архітектуру керування із використанням нечіткої логіки та ПІД-регуляторів для забезпечення балансу між глобальним слідуванням траєкторії та локальними реактивними діями. Результати моделювання підтверджують здатність системи зберігати стабільність і точність траєкторії за умов різноманітних збурень і змін у середовищі.

Ключові слова: адаптивне керування, мобільний робот, відстеження траєкторії, динамічне середовище, нечіткий-ПІД, уникнення перешкод, навігація в реальному часі

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