Adaptive Motion Planning with Artificial Potential Fields and Occupancy Grid Maps for UGVs: Dynamic and Static Target Tracking with Obstacle Avoidance

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***Abstract*—This paper explores the enhancement of the Artificial Potential Field (APF) method integrated with Occupancy Grid Maps (OGM) for unmanned ground vehicles (UGVs), focusing on dynamic and static target tracking with obstacle avoidance using Fast Hokoyu Lidar Laser Scanner. The primary objective is to refine the APF algorithm to improve the path tracing and obstacle avoidance capabilities of the Pioneer P3dX mobile robot within the CoppeliaSim simulation environment. This study incorporates the Vector Field Histogram plus (VFH+) for real-time obstacle detection and utilizes OGM for a detailed environmental representation, aiming to demonstrate the robot's ability to adapt to both static and dynamic targets effectively.**

***Index Terms*—Artificial Potential Field (APF), Occupancy Grid Maps (OGM), Vector Field Histogram, Obstacle Avoidance. '**

I. INTRODUCTION

The field of robotics has seen significant advancements in autonomous navigation and obstacle avoidance strategies. Traditional methods often struggle with dynamic environments where obstacles and targets continuously change. The APF method, which uses virtual forces to guide a robot's movement, offers a promising solution but requires enhancements to handle dynamic scenarios effectively. This research aims to address these challenges by integrating advanced sensory and mapping techniques with the APF method to improve navigation and target tracking capabilities of UGVs.

The motivation behind this research stems from the increasing demand for UGVs capable of operating in complex, unpredictable environments. As robots are increasingly deployed in areas ranging from industrial automation to urban search and rescue, the need for robust, flexible navigation systems becomes paramount. The APF method, while beneficial in its simplicity and effectiveness in certain scenarios, often falls short in dynamic environments due to its local minima problem and sensitivity to parameter settings.

This study proposes a dual approach to enhance the APF method's efficacy. First, by integrating the VFH+ algorithm, which employs a polar histogram for real-time obstacle detection, the system can dynamically adjust to sudden changes in the environment. Second, the use of Occupancy Grid Maps provides a high-resolution, grid-based representation of the environment, which significantly aids in the planning and execution of safe navigation paths.

Furthermore, the research explores the balance between attractive and repulsive forces within the APF to optimize the robot's trajectory towards its target while avoiding obstacles. By adjusting the parameters of these forces based on the robot's current state and environmental feedback, the system aims to achieve a more adaptive and resilient navigation solution.

The integration of these technologies is expected to not only enhance the robot's operational efficiency but also extend its applicability to a broader range of tasks and environments. Through rigorous simulation testing in CoppeliaSim, this paper evaluates the proposed enhancements and discusses their implications for future real-world applications.

II. LITERATURE REVIEW

Artificial potential fields (APFs) and occupancy grid maps are key techniques for adaptive motion planning in unmanned ground vehicles (UGVs). APFs use attractive and repulsive potentials to guide the robot while avoiding obstacles. However, traditional APFs suffer from local minima issues. To address this, researchers have proposed adaptive APF approaches that integrate prior path information or use additional forces to escape local minima. Occupancy grid mapping, originally developed in the 1980s, provides a probabilistic environment representation for obstacle tracking.

Recent work has focused on combining APFs and occupancy grid mapping with advanced techniques for dynamic environments. For example, model predictive control (MPC) has been used with APFs and occupancy grids to enable dynamic obstacle avoidance in real-time. Other approaches integrate APFs with fuzzy logic, deep reinforcement learning, and evolutionary algorithms for adaptive motion planning. In 3D environments, techniques like elevation mapping and traversability analysis extend 2D occupancy grids to represent complex terrain for UGV navigation. Researchers have also investigated integrating local and global planning by combining APFs for local obstacle avoidance with global search methods like A*.

The fusion of artificial potential fields, occupancy grid mapping, and advanced adaptive techniques enables robust motion planning for UGVs in dynamic environments. Continued research in this area has strong potential to enhance UGV autonomy for various applications.

III. Methodology

A. Overview of Artificial Potential Fields

The methodology for enhancing the Artificial Potential Field (APF) method involves a detailed implementation of both attractive and repulsive potential functions tailored to the dynamics of the Pioneer P3dX mobile robot. The APF method utilizes a scalar field to guide the robot's motion by assigning potential energy values to each point in the environment. These values are influenced by two main types of virtual forces: attractive forces, which pull the robot towards the goal, and repulsive forces, which push the robot away from obstacles.

The potential at a point q is given by:

$$U(q) = U_{\text{att}}(q) + U_{\text{rep}}(q)$$

where U_{att} and U_{rep} are the attractive and repulsive potentials, respectively.

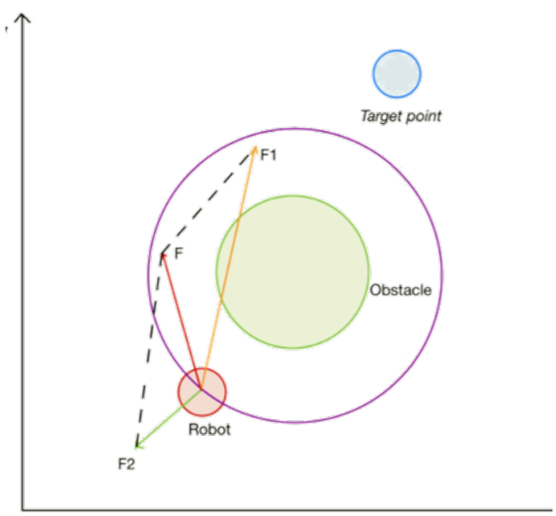

Fig. 1. Artificial Potential Field

B. Attractive and Repulsive Potential Functions

The attractive potential function is designed to have its minimum at the goal configuration, guiding the robot towards its target. This function can be modeled using a combination of quadratic (parabolic) and linear (conic) components. The quadratic component dominates when the robot is close to the goal, providing a smooth gradient, while the linear component becomes significant as the robot moves further from the goal, offering a stronger pull towards the target.

Conversely, the repulsive potential function is activated by proximity to obstacles. It is defined by parameters that dictate the influence range and the intensity of repulsion. The function ensures that the robot maintains a safe distance from obstacles, with the repulsion strength decreasing as the distance increases until it becomes negligible beyond a certain threshold.

C. Integration of Vector Field Histogram Plus (VFH+)

To enhance real-time obstacle avoidance, the Vector Field Histogram Plus (VFH+) is integrated into the APF framework. VFH+ uses a polar histogram approach to process sensor data and detect feasible paths. This method involves constructing a primary polar histogram that represents obstacle density around the robot in various directions, then simplifying this into a binary polar histogram to classify sectors as free or occupied. The VFH+ algorithm allows for dynamic adjustments based on immediate environmental changes, improving the robot's ability to navigate complex terrains.

IV. Implementation of Occupancy Grid Maps

Occupancy Grid Maps (OGM) serve as a foundational tool in mobile robotics for representing the environment in a detailed and dynamic manner. By dividing the environment into a grid, each cell within this grid is assigned a probabilistic state indicating whether it is occupied, free, or unknown. This probabilistic nature of OGM is particularly advantageous in environments where the presence and position of obstacles are subject to change or when sensor data is uncertain. The fully map obtained from the Pioneer 3-DX robot is shown below in the occupancy grid map Figure 2.

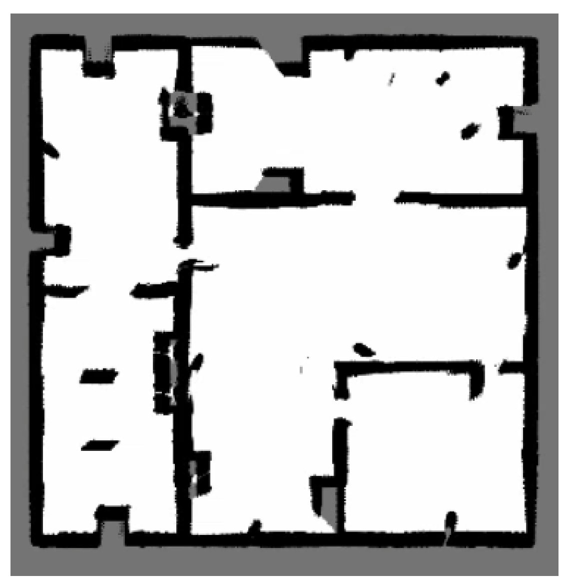

Fig. 2. Occupancy Grid Maps

A. Role of Bayesian Fusion in OGM

Bayesian Fusion is a critical process in the dynamic updating of OGM. It employs Bayes' rule in a recursive manner to refine the occupancy probability of each cell based on incoming sensor data. This method is adept at managing the inherent uncertainties in sensor measurements, allowing for a more accurate and reliable map over time. The Bayesian updating process is particularly effective when dealing with binary events, such as a cell being occupied or not, simplifying the computation and making it suitable for real-time applications.

Bayesian updating is used to refine the map based on new sensor data:

$$p(x \mid z) = \frac{p(z \mid x) \cdot p(x)}{p(z)}$$

where $p(x \mid z)$ is the posterior, $p(z \mid x)$ is the likelihood, $p(x)$ is the prior, and $p(z)$ is the evidence.

B. Log-Odds Representation

The implementation of Bayesian Fusion in OGM is significantly optimized through the use of log-odds ratios. This representation transforms the Bayesian updating process into a straightforward addition operation, where the log-odds value of a cell's occupancy probability is updated by adding the log-odds value derived from the new sensor measurement. This approach not only simplifies the computational process but also ensures that the updating mechanism is efficient and scalable for large maps.

C. Gradient-Based Motion Control

The robot's movement is controlled by following the negative gradient of the potential function, which acts as a force directing the robot towards areas of lower potential energy. The control method often used is the steepest descent method, where the robot's speed is proportional to the gradient. This approach ensures that the robot moves in the direction that optimally reduces the potential energy, thereby guiding it towards the goal while avoiding obstacles.

D. Handling Local Minima and Oscillations

One of the challenges with APF is the occurrence of local minima, where the robot gets stuck in a position that is not the goal due to a balance of attractive and repulsive forces. To address this, additional strategies such as applying a small perpendicular force or implementing random movements can be used to help the robot escape from these local minima. Moreover, the methodology includes tuning the step size in the gradient descent to minimize oscillations and ensure smoother motion.

E. VFH+ and OGM Integration

The integration of VFH+ into the APF framework introduced several key improvements. The binary polar histogram, a feature of VFH+, used two thresholds to classify sectors as free or occupied, improving the smoothness of motion planning. Additionally, the masked polar histogram accounted for the robot's kinematic constraints by masking unreachable directions, ensuring that selected paths were feasible for the robot's capabilities. OGM's role in the enhanced APF algorithm was pivotal. By representing the environment as a grid where each cell indicates if the space is occupied, free, or unknown, OGM allowed for a more accurate environmental representation. This accuracy was crucial for calculating the attractive and repulsive potential functions, leading to improved path planning accuracy.

F. Navigation and Obstacle Avoidance

In scenarios involving static targets, the robot demonstrated an exceptional ability to navigate to the goal location without any collisions. The attractive potential function effectively guided the robot towards the goal, while the repulsive potential function ensured avoidance of obstacles. The VFH+ algorithm played a crucial role in real-time obstacle detection and avoidance. By constructing a primary polar histogram from sensor data, VFH+ identified feasible paths through lower-density areas, significantly enhancing the robot's ability to maneuver in complex environments.

For dynamic targets, the robot's performance was equally impressive. The VFH+ algorithm's real-time processing of sensor data allowed the robot to dynamically adjust its trajectory in response to moving targets and obstacles. This adaptability was further supported by the OGM, which provided a detailed and updatable representation of the environment, enabling precise calculations of potential fields and efficient path planning

V. Results

The implementation of the enhanced Artificial Potential Field (APF) algorithm, augmented with the Vector Field Histogram plus (VFH+) and Occupancy Grid Maps (OGM), underwent comprehensive testing in a simulated environment using CoppeliaSim. These simulations aimed to evaluate the algorithm's effectiveness in navigating a mobile robot towards both static and dynamic targets while avoiding various obstacles. The integration of VFH+ and OGM into the APF algorithm has shown significant improvements in the robot's navigation capabilities, particularly in real-time adaptation, obstacle avoidance, and path planning accuracy.

VI. Conclusion

The project successfully demonstrated the effectiveness of the APF method enhanced with VFH+ and OGM in a simulated environment. These technologies together facilitated dynamic and static target tracking with efficient obstacle avoidance, showcasing the robot's ability to adapt to real-time changes in the environment. Further improvements could include refining the APF algorithm's parameters and integrating more advanced sensor technologies to handle more complex scenarios.

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