

Improvement of the APF-RRT*-Connect Algorithm for Efficient Path Planning in 3D Environments

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Abstract

This paper presents an improved Artificial Potential Field - Rapidly-exploring Random Tree Star-Connect algorithm for three-dimensional environments. The improved method integrates the Artificial Potential Field during path generation to optimize each newly generated node in real-time. This approach reduces the number of node optimization processes, collision detections and optimizes the target nodes in the attractive potential field. Through Matlab simulation, the paper compares the path length and planning time of the traditional Artificial Potential Field - Rapidly-exploring Random Tree Star-Connect algorithm and the improved algorithm. The results indicate that the improved algorithm can find shorter paths in less time and enhances the smoothness of the path.

Keywords: Artificial potential field, Rapidly-exploring random tree, Three-dimensional environments, Real-time

1. Introduction

Path planning plays a vital role in the three-dimensional environment, which is widely used in industrial robots, drones, medical surgery, virtual reality and other fields to achieve efficient, safe and smooth path planning. However, traditional algorithms encounter many challenges in complex three-dimensional environments, including the computational complexity of high-dimensional search, the real-time requirements of dynamic environments, the trade-off between path smoothness, and the robustness under uncertain conditions. Therefore, the research focus on designing algorithms that can quickly generate high-quality paths. This paper proposes an improved APF-RRT*-Connect algorithm which improves the sampling and search strategies to optimize the attraction target points and reduce the number of collision detections.

This paper is organized as follows. The second section introduces the principles and formulas of the related algorithms. In the third section, the comparative experimental simulation of the traditional algorithm and the improved algorithm is carried out, and the performance of the improved algorithm is verified. The fourth section summarizes the main content of the article and puts forward the future prospects.

2. The Principles and Improvement Methods of the APF-RRT*-Connect Algorithm

The APF-RRT*-Connect algorithm adopts the artificial potential field (APF) method to optimize the path generated by the RRT*-Connect algorithm. The APF-

RRT*-Connect algorithm can reduce the path length to a certain extent, while it increases the time and optimization steps required for path planning. Therefore, the improved APF-RRT*-Connect algorithm is proposed, which can reduce the path planning time, and also reduce the path length and optimization steps.

2.1. The RRT*-Connect algorithm

The RRT*-Connect algorithm [3] is an algorithm that gradually optimizes the path to approach the optimal solution while quickly finding a feasible solution. The RRT-Connect algorithm [2] significantly improves the search efficiency by extending the bidirectional tree (starting tree and target tree), so that it can quickly find an initial feasible path. The principle is shown in Fig.1. The RRT*-Connect retains this two-way expansion mechanism and ensures the ability to quickly find paths in complex high-dimensional spaces.

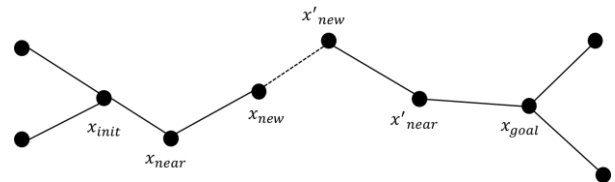


Fig.1. RRT-Connect algorithm

The RRT*-Connect gradually optimizes the path by re-selecting the reconnection of the parent node and the nearby nodes [1] to ensure that the final path can gradually approach the global optimal solution. The principle is shown in Fig.2 and Fig.3.

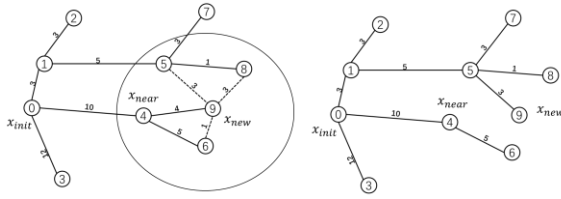


Fig.2. Reselecting parent nodes

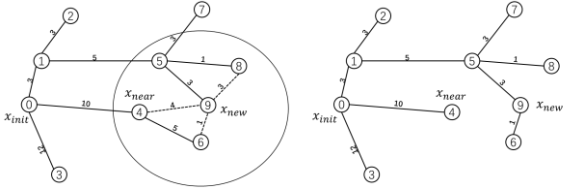


Fig.3. The process of reconnecting nearby nodes

2.2. The APF-RRT*-Connect algorithm

(1) Artificial Potential Field

Artificial Potential Field (APF) [5] is a classical robot path planning algorithm, which guides the robot movement by constructing a virtual 'potential field'. The potential field consists of two parts : attractive potential field and repulsive potential field. The gravitational potential field guides the robot to the target position, while the repulsive potential field keeps the robot away from obstacles, so as to achieve the purpose of obstacle avoidance and target arrival in path planning.

The attractive potential field U_{att} is typically defined as a quadratic function of the Euclidean distance between the target point and the current robot position. The corresponding attractive force F_{att} is the negative gradient of the attractive potential field.

$$\begin{cases} U_{att} = \frac{1}{2}k_{att}|q - q_{goal}|^2 \\ F_{att} = -\nabla U_{att} = -k_{att}(q - q_{goal}) \end{cases} \quad (1)$$

Where k_{att} represents the scaling factor of the attractive potential field, which controls the magnitude of the attractive force. q denotes the current position, and q_{goal} represents the target position.

The repulsive potential field U_{rep} is typically defined as an inverse function of the distance between the robot and obstacles, generating a repelling effect near obstacles. The corresponding repulsive force F_{rep} is the negative gradient of the repulsive potential field.

$$U_{rep} = \begin{cases} U_{rep1}, & \text{if } |q - q_{obs}| \leq d_0 \\ 0, & \text{if } |q - q_{obs}| > d_0 \end{cases} \quad (2)$$

$$U_{rep1} = \frac{1}{2}k_{rep} \left(\frac{1}{|q - q_{obs}|} - \frac{1}{d_0} \right)^2 \quad (3)$$

$$F_{rep} = \begin{cases} F_{rep1}, & \text{if } |q - q_{obs}| \leq d_0 \\ 0, & \text{if } |q - q_{obs}| > d_0 \end{cases} \quad (4)$$

$$F_{rep1} = k_{rep} \left(\frac{1}{|q - q_{obs}|} - \frac{1}{d_0} \right) \frac{1}{|q - q_{obs}|^3} (q - q_{obs}) \quad (5)$$

Where k_{rep} represents the scaling factor of the repulsive potential field, q_{obs} denotes the position of the obstacle, and d_0 is the influence range of the repulsive potential field.

The total potential field force acting on a node is the vector sum of the attractive force and the repulsive force.

$$F = F_{att} + F_{rep} \quad (6)$$

(2) The APF-RRT*-Connect algorithm

The process of the traditional APF-RRT*-Connect algorithm [4] is : after the RRT*-Connect algorithm generates a path, the Artificial Potential Field (APF) method is used to optimize the path. When calculating the attractive force and attractive potential field, the first point on the path is set as the current position q , and the next point is set as the target point. Once a point's calculations are complete, the next point is set as the current position q and the process continues iteratively until the second-to-last point in the path.

When calculating the repulsive force and repulsive potential field, the current position q is set based on the first point to the last point on the path, and the obstacle position q_{obs} is determined from surrounding obstacle information. The resultant force at each point is the vector sum of the attractive and repulsive forces. Its schematic diagram is shown in Fig.4.

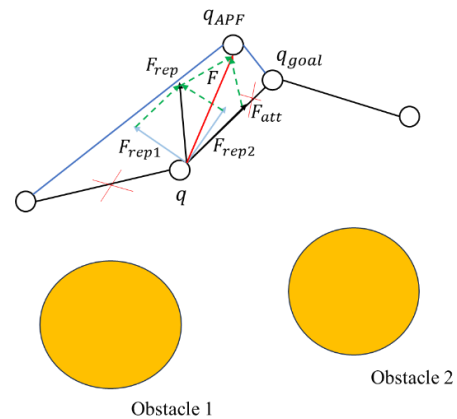


Fig.4. APF-RRT*-Connect Algorithm

(3) The improved APF-RRT*-Connect algorithm

The improved APF-RRT*-Connect algorithm achieves path optimization by incorporating the Artificial Potential Field (APF) method during the path generation process. Based on the bidirectional tree generation process of the RRT*-Connect algorithm, one tree is used as the reference. The newly generated node x_{new} of this tree is set as the current position q , while the newly generated node of the other tree is set as the target position q_{goal} . The attractive force acting on the nodes of the first tree is then calculated. Subsequently, the second tree is used as the reference, and its newly generated node x'_{new} is set as the current position q , while the newly generated node of the other tree is set as the target position q_{goal} , to calculate the attractive force acting on the nodes of the second tree.

When calculating the repulsive force and repulsive potential field, forces on the nodes of both trees need to be calculated separately. First, the nodes of the first tree are treated as the current position q to compute the forces acting on its nodes, followed by treating the nodes of the second tree as the current position q to compute the forces acting on its nodes. Finally, the resultant forces acting on the nodes of the first and second trees are calculated separately. Its schematic diagram is shown in Fig.5.

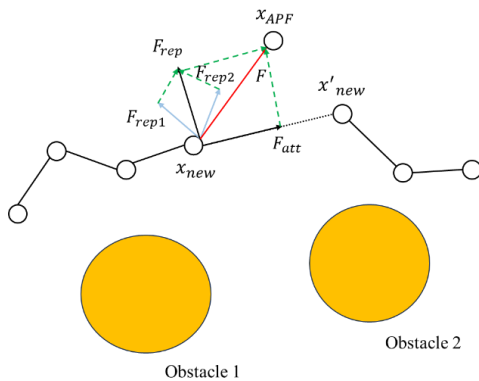


Fig.5.Improved APF-RRT*-Connect Algorithm

3. Simulation

To validate the effectiveness of the improved APF-RRT*-Connect algorithm, a simulation platform was built using MATLAB to compare the performance of the improved algorithm with the traditional algorithm, thereby verifying the efficiency of the improved algorithm. The validation experiments were conducted in the same three-dimensional environment. The map of the 3D environment has a range of $1000 \times 1000 \times 1000$, where cyan blocks represent cuboid obstacles, blue blocks represent cylindrical obstacles, and green blocks represent spherical obstacles. The starting point coordinates are $(0, 0, 0)$, and

the target point coordinates are $(600, 600, 200)$. The golden line represents the path planned by the improved algorithm, while the red line represents the path planned by the traditional algorithm. The simulation results are shown in Fig.6. From the comparison in the figure, it can be observed that in the 3D environment, compared to the traditional algorithm, the improved algorithm has fewer turning points, a shorter path, and a smaller search range in invalid regions.

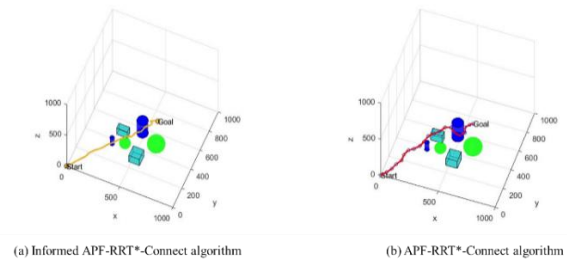


Fig.6. Simulation in 3D environment

After 30 repeated experiments, the path planning time and path length of the two algorithms were summarized, and the results are shown in Fig.7 and Fig.8. Figure 7 displays the comparison of path planning times after 30 repeated experiments for both algorithms, while Figure 8 shows the comparison of path lengths. It is evident that in the 3D environment, the improved algorithm requires less time for path planning and generates shorter paths.

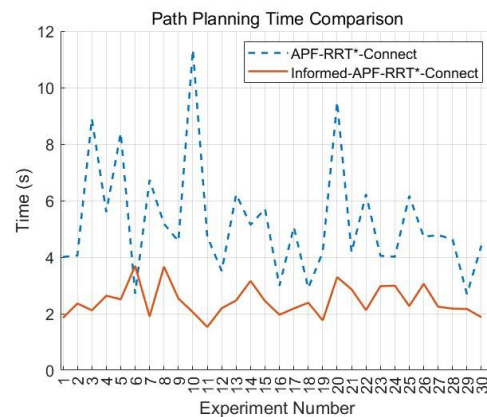


Fig.7. Comparison of Path Planning Time

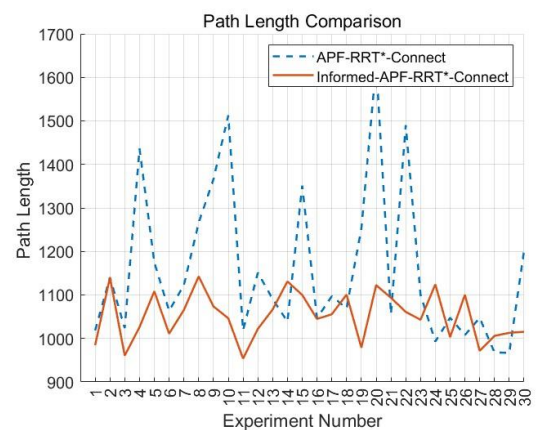


Fig.8. Comparison of Path Length

The average path planning time of the improved algorithm over 30 experiments is 2.44896367 seconds, which is approximately 53.29% shorter than the 5.24300037 seconds of the traditional algorithm. The average path length of the improved algorithm is 1052.172907, which is about 9.16% shorter than the 1158.33075 of the traditional algorithm.

4. Conclusion

This paper introduces the APF-RRT*-Connect algorithm and presents its improvements. By modifying the role of the artificial potential field (APF) in the path generation process, the time required to generate paths is reduced, and the generated paths are shorter. During the path generation process, the latest node of one tree is used as the current node in the artificial potential field, while the latest node of the other tree is used as the target node to calculate the attraction between the two points. This approach reduces the randomness of node generation, thereby decreasing the number of redundant nodes, avoiding blind exploration of meaningless areas, and ultimately reducing path planning time and extra collision detection. Finally, a comparative experiment between the improved APF-RRT*-Connect algorithm and the original APF-RRT*-Connect algorithm was conducted in Matlab. The results show that the improved APF-RRT*-Connect algorithm requires less time to generate paths and produces paths with lower costs.

Although the improved algorithm reduces path planning time, the additional calculations introduced by the artificial potential field may still increase overall computational complexity in high-dimensional and complex environments, especially when obstacles are dense or large in scale. In the future, we plan to reduce computational complexity by improving the artificial potential field model, thereby further enhancing computational efficiency.

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Authors Introduction

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