International Journal of Engineering Research And Management (IJERM)
ISSN: 2349- 2058, Volume-12, Issue-03, March 2025

Full Coverage Anti-Winding Algorithm of Tethered Inspection Robot Based On Adaptive Path Planning

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***Abstract*—In the context of bottom plate inspections for oil tanks, tethered unmanned vehicles (SLUVs) encounter cable entanglement issues due to the complex environment created by multiple support columns within the tanks. This paper introduces an innovative cable anti-entanglement algorithm based on adaptive path planning, aiming to optimize the inspection path of SLUVs in multi-column oil tank environments to achieve efficient and comprehensive bottom plate inspections. The core idea of the algorithm is to intelligently plan the SLUV's motion trajectory to avoid potential entanglement risks with support columns while ensuring comprehensive scanning of the tank's bottom plate. We conducted a series of simulations and real-world tests to verify the algorithm's effectiveness. The results show that the algorithm significantly improves inspection efficiency and prevents work interruptions due to entanglement, thereby greatly reducing the need for manual intervention. This study not only offers an efficient solution for oil tank bottom plate inspections but also opens up new possibilities for tethered robots in similar multi-column environments. With further research and development, the technology's application range is expected to expand to more industrial and exploratory fields, providing robust technical support for automated operations in complex environments.**

***Index Terms*—Tethered unmanned vehicles; Cable entanglement; Adaptive path planning; Multi-column oil tank environments; Bottom plate inspections; Inspection efficiency.**

I. INTRODUCTION

With the continuous development of the petroleum industry, oil tank storage has become an indispensable part of the sector. However, tank safety remains one of the significant challenges faced by the industry. Inside oil tanks, there are often potential safety hazards such as flammable gas accumulation, corrosion, and leaks, making regular inspection and maintenance essential. There are currently many types of tanks used to store volatile liquids, including:1. Fixed-roof oil tanks; 2. External floating-roof tanks; 3. Internal floating-roof tanks; 4. Domed external floating-roof tanks; 5. Horizontal storage tanks; 6. Pressure vessels;7. Variable vapor space tanks[1]. Among these, the most common tanks are fixed-roof and internal floating-roof tanks. Both are cylindrical with their axes perpendicular to the foundation. The scenario described in this paper involves a large external floating-roof tank supported internally by multiple support columns. Traditional inspection methods often involve extensive manual operations, which are not only costly but also pose safety risks[2].To enhance inspection efficiency and minimize safety risks to personnel, various robotic technologies have been researched and applied in recent years to carry out oil tank inspections. Robotic technologies are particularly favored for their efficiency and safety in inspecting large oil tanks.

Jun Tu et al.[3]designed an automatic navigation magnetic flux leakage detection robot for rapid multi-loop inspections of tank bottoms. Yinchu Wang et al.[4]proposed a path planning and positioning algorithm for a large storage tank bottom inspection robot, designing a predefined spiral path based on the tank bottom's shape.[5] introduced a climbing robot for inspecting tank sidewalls for damage. All of these robots require the installation of magnetic adhesion devices to ensure the robots can independently enter and exit oil tanks.

This study focuses on developing an adaptive path-planning tethered unmanned inspection vehicle specifically designed to conduct comprehensive bottom plate inspections within oil tanks containing multiple support columns, while avoiding data cable entanglement issues. This challenge primarily arises from the tank's complex structural layout, particularly the unique obstacle environment formed by multiple support columns at the tank's bottom, which makes the inspection vehicle prone to cable entanglement during its tasks, affecting operational efficiency and safety.Against this backdrop, this study introduces an innovative algorithm that ensures the unmanned vehicle can efficiently and safely complete comprehensive inspections of the oil tank bottom plate through precise path planning. The algorithm is designed to optimize the vehicle's movement path to adapt to the tank's complex, multi-column environment, thereby enhancing the vehicle's operational efficiency and safety.

The following sections of this paper will provide a detailed overview of correlation studies, experimental methods, experimental results, and conclusions, aiming to present a new technical solution for the field of oil tank inspections. This solution seeks to improve the efficiency and safety of oil tank inspections, minimize manual intervention, and support safety management and operational efficiency in the petrochemical industry.

II. RELATED WORK

A. *Coverage Path Planning e*

Coverage Path Planning (CPP) aims to determine the trajectory for robots or other mobile agents to fully cover a given area. This task is crucial in many robotic applications, including vacuum cleaner robots, painting robots, Autonomous Underwater Vehicles (AUVs), demining robots, lawnmowers, automatic harvesters, and window

Manuscript received March 17, 2025

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cleaners. Research on the CPP problem has made significant progress and has been applied across various fields. The goal of CPP is to design a path-planning algorithm that enables the robot to cover every reachable area in the environment, which is crucial for ensuring the comprehensiveness and effectiveness of the task. Solutions to CPP must consider factors such as the complexity of the environment, the robot's mobility and efficiency, and obstacles that may be encountered during coverage.

A significant body of research has focused on solving CPP problems, including the design and optimization of path-planning algorithms, improvements in environment modeling methods, and optimization of robot control strategies. These studies aim to enhance the efficiency and comprehensiveness of the coverage path while reducing the cost and risks associated with robot movement. Through research and application of CPP, robotics can be effectively leveraged to solve various real-world problems, increasing productivity and task quality. Continuous progress in this field will bring more opportunities and innovations across various robotic applications.

Yakoubi et al.[6] and Lamini et al.[7] employed the cell decomposition method to model the environment of mobile robots. They assigned identifiers and reference points to each subregion based on the characteristics of the modeling, and established connectivity relationships between the subregions. Using Genetic Algorithm (GA), they encoded each subregion and set up reference point information both between and within subregions. The GA was then used to obtain the optimal coverage sequence, achieving partial coverage within each subregion through a back-and-forth motion pattern. This approach effectively transformed the complete coverage problem of mobile robots into a Traveling Salesman Problem (TSP). Furthermore, the relationship between GA parameters and search capability was thoroughly investigated, leading to the identification of the optimal GA parameters. The key to this method lies in decomposing the environment into multiple subregions, optimizing the coverage sequence for each subregion using GA, thereby maximizing coverage efficiency. By converting the problem into a TSP, existing TSP solving algorithms can be leveraged to further optimize the path planning of mobile robots, ensuring comprehensive environment coverage while minimizing motion costs and time consumption.

Junnan Song et al.[8] proposed an online coverage path planning algorithm named ε⋆, specifically designed for path planning in unknown environments for autonomous vehicles. This algorithm is based on the concept of an Exploratory Turing Machine (ETM) and generates coverage paths in real-time using Multiscale Adaptive Potential Surfaces (MAPS), thereby avoiding local extremum issues and ensuring complete coverage. Experimental results demonstrate that this algorithm outperforms existing methods in terms of path length and number of turns. Its advantages include high computational efficiency, the ability to generate the desired back-and-forth motion paths, and the avoidance of local extremum problems, although it may rely heavily on sensors in complex environments. Tan, Chee Sheng et al.[9] conducted a comprehensive review of CPP algorithms based on classical and heuristic approaches, listing the elements of various techniques and analyzing and comparing their advantages and disadvantages. The challenges in CPP, such as coverage efficiency and collision avoidance, were rigorously assessed, considering typical functions like area coverage, path length, travel time, revisit rate, and energy usage. Fu, J. et al.[10] proposed the FCPPR framework for solving multi-objective constrained FCPP problems in obstacle-constrained environments. This method takes into account multiple objectives, including coverage, overlap, trajectory length, and total accumulated turning angle, providing feasible path planning.

Bormann R [11] analyzed four mainstream offline coverage path planning methods: Morphological decomposition, distance transform-based image segmentation, Voronoi diagram-based image segmentation, and data-driven segmentation. Morphological decomposition has the advantages of being simple and easy to implement, and provides some robustness against noise. However, it can be influenced by the parameters of the morphological operations, potentially resulting in suboptimal image segmentation for complex structures.Distance transform-based image segmentation can improve segmentation accuracy to some extent and has certain advantages for images with complex structures. However, this method requires preprocessing and feature extraction, leading to high computational complexity. Moreover, it is sensitive to the choice of initial points. Voronoi diagram-based image segmentation has certain advantages for images with complex structures. However, this method requires image preprocessing and feature extraction, leading to high computational complexity. Additionally, it is sensitive to the choice of initial points. Data-driven segmentation can effectively adapt to various image types and complex structures, offering high accuracy and robustness. However, it requires substantial training data and computational resources, and model tuning and optimization are relatively complex.Each of these methods has its own merits and plays a significant role in the CPP field.

B. *Tethered Robots*

In most scenarios, untethered robots have been widely used, whereas research on tethered robots is relatively limited in comparison.[12] Research has been conducted on tethered robots. However, all previous work addressing path planning and tether navigation has focused on navigating from a single given source to a single target navigation point. The primary emphasis has been on finding the shortest path and switching between multiple navigation points while avoiding entanglement and utilizing the limited tether length. Building on this,[13] designed a climbing robot and proposed an algorithm to find fixed homotopy ascent/descent paths. This allowed the climbing robot to perform round-trip tasks in complex environments with obstacles, minimizing the likelihood of tether entanglement. However, this method performs best only when the environment remains constant.[14] improved upon the work in[13] by enabling real-time detection of environmental changes. The algorithm recalculates new homotopy paths based on sensor-detected environmental changes to prevent the previously planned paths from becoming unusable, ensuring real-time and safe navigation. Despite these advancements, tethered robot navigation still has the potential for entanglement.[15]

introduced a low-cost and robust tether management system that doesn't require an environmental map for operation. It provides several advantages such as positioning and robot recovery, enabling real-time tether monitoring to detect entanglement. By tracking and localizing the tether within line of sight, it can execute untangling operations. Building on this foundation, the system also allows for coordinated work among multiple autonomous robots.

III. EXPERIMENTAL METHODS

In this study, a tethered robot is used. The oil tank scanning method requires pre-generating a 2D map of the tank bottom using the Cartographer mapping algorithm. With this prior map and the robot's starting position, accurate cell decomposition and genetic algorithms are employed for path planning, enabling the completion of the global path for the entire scanning process. The robot is then lowered into the tank bottom via a central entry point from the top using a data cable. Navigation algorithms subsequently send navigation points to the robot's move_base node to complete the entire scanning task. This experiment was conducted in a simulated oil tank environment. The environment was accurately constructed to reflect the structural characteristics of a typical oil tank, including multiple randomly distributed support columns.

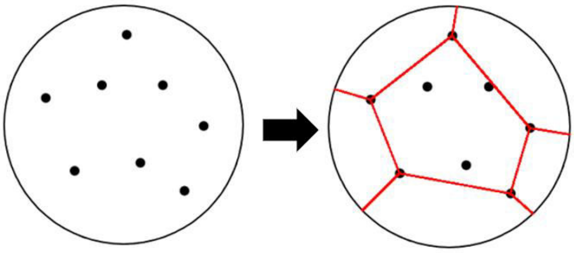
A. Cell Decomposition

Given the specific characteristics of this study's environment, we incorporated the advantages of mainstream cell decomposition methods. The key to this approach is ensuring that each cell is a convex polygon, so the robot won't encounter anomalies when moving inside. Smaller cells are merged to reduce the number of partitions. Since each partition is generated based on the obstacles, no support columns exist within the partitions, thus preventing potential entanglement. This integrated approach aims to leverage the strengths of mainstream methods while addressing challenges the robot may encounter during scanning. As a result, the scanning efficiency and safety are improved.

In this study's cell decomposition, the Graham scan method was used to compute the convex hull. Proposed by Graham in 1972, this method can solve the convex hull problem with a time complexity of O(nlogn), where n is the size of the point set. The steps are as follows: First, identify the reference point, which is always on the convex hull since it is the point with the smallest y-coordinate. Next, sort all other points by polar angle relative to the reference point.In a plane, the cross product of two vectors $\vec{a}\times\vec{b}$ is defined as absinθ, where θ is the angle (up to 180°) that $\vec{a}$ rotates to $\vec{b}$. If $\vec{a}$ rotates clockwise to $\vec{b}$, then θ > 0; otherwise, θ < 0. If $\vec{a}$ = (x_1,y_1) and $\vec{b}$ = (x_1,y_1), then $\vec{a}\times\vec{b}$ = x_1 y_2 – x_2 y_1 . Therefore, to determine the ordering of two points A and B relative to the pole O, we compute the cross product $\overrightarrow{(OA)}\times\overrightarrow{(OB)}$. If $\overrightarrow{(OA)}$ rotates clockwise to $\overrightarrow{(OB)}$ (where θ > 0), the cross product is positive, and point A is positioned before point B. Conversely, if θ < 0, A is positioned after B. If O,A,and B are collinear, the point closest to O is removed. Ultimately, this method identifies all the vertices of the convex hull.

In this study, let the number of support points be n. If n is less than or equal to 3, return directly. Otherwise, initialize an empty stack and push the first two points onto it. For each subsequent point B, let the top of the stack be A and the next point on the stack be O. If vector $\overrightarrow{(OA)}$ rotates clockwise by an angle θ > 0 to align with the direction of vector $\overrightarrow{(OB)}$, then B is pushed onto the stack directly. Otherwise, a non-left-turn condition is detected, and A is popped from the stack. This process is repeated until there are fewer than two elements in the stack or a left turn is formed. B is then pushed onto the stack. The final set of points remaining in the stack will be the vertices of the convex hull.

By computing the convex hull of the environment, the feasible region of the robot can be determined, allowing the planning of a safe and efficient movement path. In this study, the internal support pillars within the oil tank are irregularly distributed. The outermost ring of support pillars is identified first, which, together with the tank wall, forms partitions, as illustrated in Figure 1. The red lines represent the convex hull calculation results and the partitions formed with the tank wall.



Figue1 Determine the outermost support column and partition it with the outer profile

Using the aforementioned method, the outermost partition is first defined. The same steps are then applied to the inner nodes to delineate partitions between the inner nodes and the outer convex region, as illustrated in Fig 2. This process will yield an array of polygons for each partition and the coordinates of the center point for each partition. If needed, smaller partitions can be merged with other partitions to reduce their total number.

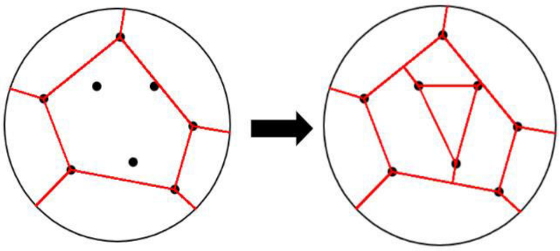


Figure2 Final partition result

B. Genetic algorithm solves traversal interval

Based on the final partition results, the order of traversing the regions is determined using the Genetic Algorithm (GeneticTSPSolver). Considering the constraint of cables, the robot cannot move directly from one partition to the next for scanning, as this may result in cable entanglement.Therefore, the robot needs to find a suitable traversal order, considering path backtracking to avoid entanglement between pillars and cables, ultimately returning to the initial position. During this process, it is crucial to compute the shortest path that traverses all partitions to ensure full coverage and minimize overall travel distance. This task can be transformed into a traveling salesman problem and solved using a genetic algorithm. When using this algorithm to determine the region traversal sequence, the sequence can be represented as a permutation, where each element represents a region. Assuming there are n regions, let $k = (k1\ , k2\ , \dots , kn\ )$ denote a chromosome encoded as integers, and $Dkikj$ represent the distance from region ki to region kj. The fitness of this individual is defined as:

$$\text{Fitness} = \frac{1}{\sum_{i=1}^{n-1}(Dkikj + Dknk1)}$$

(1)

In other words, the fitness function is the inverse of the total distance needed to traverse all n regions and return to the starting point.

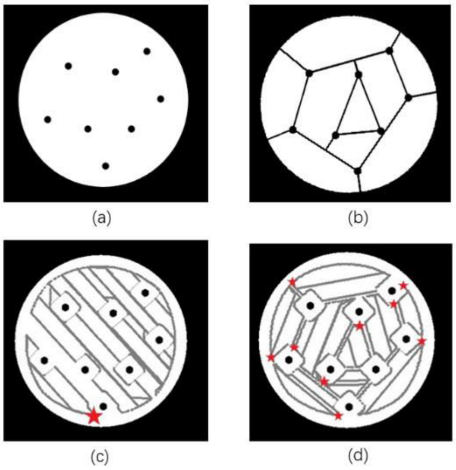
Selection is performed based on the fitness of each individual, and the selected individuals produce offspring through crossover operations. To enhance population diversity, some genes of an individual are randomly modified with a certain probability. Through selection, crossover, and mutation operations, a new generation of individuals is created, and finally, the individual with the highest fitness is chosen from the population as the solution to the problem.

After determining the traversal sequence for each region using the aforementioned method, proceed to cover each region one by one. When determining the starting point within a region, consider the distance from the region's center point to each vertex and select the vertex closest to the center point as the starting point. Inside the region, generate an arched back-and-forth path, adjusting the path line density based on the robot's size and the expansion radius around obstacles to avoid collisions. Finally, convert the path points into robot navigation coordinates using the resolution of the prior map and initial localization information, then transfer them to the robot navigation controller via the publishing system.

IV. EXPERIMENTAL RESULTS

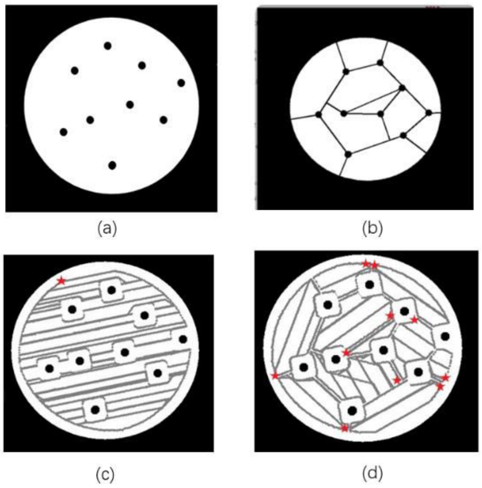
To verify the effectiveness and superiority of the algorithm proposed in this paper, the path planning results of this experiment were compared with traditional full-coverage methods, using the Gazebo simulation platform to conduct a series of validation experiments. The simulation was carried out in a closed space equipped with multiple pillar obstacles, simulating the internal environment of an actual oil tank. In this environment, the robot was first deployed to build the environmental map, and then accurate path planning was performed based on the map information. In the experiment, the robot's starting point was located at the center of the space to optimize path length and reduce redundant movement. Finally, the performance differences between the traditional full-coverage scanning algorithm and the algorithm presented in this study were compared.

The simulation results, as shown in Figures 3 to 5, illustrate: (a) the original map, (b) the results of region partitioning, (c) the path from the traditional full-coverage algorithm, where the red pentagram indicates the starting point of full-coverage scanning, and (d) the path planned by this study's algorithm, where the red pentagram indicates the starting point of scanning for each partition. In Figure (c), although the traditional full-coverage scanning method can achieve complete space coverage, this approach may lead to cable entanglement with pillars in actual operations when considering the robot's cable constraints. In contrast, the algorithm presented in this study effectively avoids the risk of entanglement through intelligent partitioning and backtracking mechanisms. Each partition scan ensures path optimization while also guaranteeing safe navigation in obstacle-free partitions, thus demonstrating the significant advantages of this algorithm in enhancing automation and safety in oil tank inspection processes.


(a) (b)

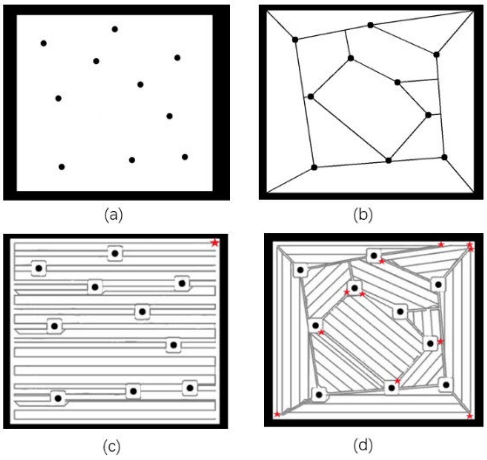
(c) (d)

Figure3 Circular area planning example diagram


(a) (b)

(c) (d)

Figure4 Circular area planning example diagram


(a) (b)

(c) (d)

Figure5 Square area planning example diagram

V. CONCLUSIONS

This study aims to address the path planning challenges faced by tethered robots performing full-coverage scanning in the complex internal environment of oil tanks. Recognizing that traditional path planning algorithms may cause cable entanglement in practical applications, this paper proposes an innovative path planning strategy and verifies its effectiveness through simulation experiments.

The experiments utilized the Gazebo simulation platform in a simulated enclosed space containing multiple pillar-like obstacles to replicate the real internal environment of oil tanks. In this environment, the robot first builds a map, then performs path planning based on the map information, and finally executes navigation within the simulation to observe its performance. The results show that compared to traditional full-coverage algorithms, the proposed algorithm significantly reduces the risk of cable entanglement while ensuring high coverage.

The core advantage of the algorithm in this study lies in the introduction of convex hull-based region partitioning and a path backtracking strategy. Through this approach, the algorithm can intelligently divide regions without obstacles and plan a path that avoids cable entanglement. After completing the scan of each partition, the algorithm considers the optimal path to the next partition to prevent entanglement while ensuring comprehensive coverage. In simulation experiments, the paths planned by this study's algorithm demonstrate efficient space utilization and accurate path planning.

Ultimately, this study not only presents an efficient and reliable path planning method but also provides practical guidance for the design and application of tethered robots. Future work will further explore path planning algorithms in different environments and will test and optimize the proposed algorithm in real oil tank inspection scenarios. Moreover, considering the complex and dynamic nature of real-world operating environments, future research will also focus on improving the algorithm's robustness to handle more unforeseen environmental variables, further promoting the application of robotics in critical industrial sectors such as oil tank inspection.With these efforts, the path planning strategy proposed in this study will contribute to achieving higher levels of automation and safety, bringing significant economic and safety benefits to the petrochemical industry.

ACKNOWLEDGMENT

The paper is not supported by any project.

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