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Research on Hull Design and Path Planning of Unmanned Garbage Collection Boats in Small Water Areas

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Abstract

With the acceleration of urbanization, the pollution problem caused by floating debris on the water surface of small water areas such as artificial lakes in parks and landscape water systems has become increasingly prominent. Meanwhile, the traditional manual cleaning methods suffer from low efficiency and high costs. To address this issue, this paper develops a catamaran-type unmanned surface vessel (USV) for garbage collection, which is suitable for small enclosed water areas, and focuses its research on the hull design and path planning of the USV. This paper constructs a set of regional full-coverage path planning methods, which provides algorithmic support for the comprehensive cleaning of water surface garbage. Simulations are carried out on MATLAB, and prototype experimental verification is completed, thus designing an effective path planning scheme for USVs to perform garbage collection tasks in small water areas.

Keywords

Unmanned Ship; Hull Design; Path Planning; MATLAB.

1. Introduction

Many developed countries began to focus on water pollution control at an early stage, and have launched a variety of intelligent water surface cleaning vessels through sustained investment in research and development resources.

In 2016, RanMarine Technology, founded by South African entrepreneur Richard Hardiman, developed the Waste Shark, an unmanned water surface cleaning vessel designed to remove floating garbage on and under the water surface through autonomous navigation technology. Powered by electricity and featuring a bionic design, it can collect 180 kilograms of garbage in a single operation, and is also equipped with water quality monitoring sensors to collect environmental data.

In 2018, the Piranha cleaning vessel, a multi-functional water surface cleaning device developed by Clean Earth Rovers of the United States, places greater emphasis on flexibility and targeting in its design, making it particularly suitable for cleaning needs in specific scenarios such as docks and ports [2].

At present, the cleaning of floating garbage on small water areas still mostly relies on the traditional manual salvage method. Manual cleaning is not only inefficient and hard to meet the cleaning demands of numerous and scattered small water areas, but also has potential safety hazards during operation, with labor and time costs rising year by year [1]. The limitations of manual cleaning are even more prominent in special environments such as narrow river channels and deep water areas. Therefore, developing a floating garbage collection vessel suitable for small water areas to realize

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automated and intelligent cleaning operations has become an urgent need to solve the pollution problem of small water areas [3].

2. Construction of the Unmanned Vessel Control System Platform

2.1 Hull Structure Design.

The small unmanned vessel for water surface waste collection researched in this paper adopts a catamaran as its core hull configuration [4]. Connected by a linking rod between two pontoons, the catamaran features a large gap between the pontoons, leading to better adaptability and higher stability. It can balance the external force of the trawl net to prevent rollover, and the gap between the pontoons can naturally gather floating waste without the need for additional power for waste collection. Additionally, it boasts the advantages of a shallow draft, good trafficability, high collection efficiency and low energy consumption [5].

The small catamaran unmanned vessel for water surface waste collection in this study adopts a modular hull design, with the goal of efficiently cleaning up floating water surface waste. All components cooperate to ensure operational performance, and its specific structure is shown in Fig. 1, where 1 denotes the hull, 2 the linking rod, 3 the cabin cover, 4 the battery box, 5 the thruster, and 6 the trawl net.

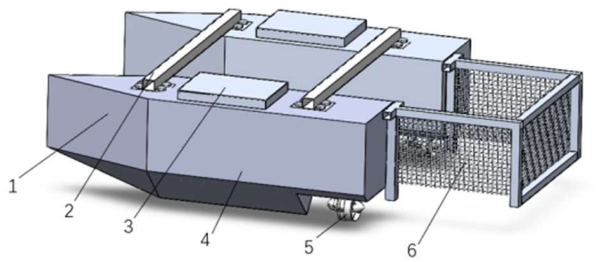

Fig. 1 Hull structure diagram

2.2 Unmanned Vessel Power Module

The main resistance forces acting on the unmanned surface vessel for water garbage cleaning designed in this study are frictional resistance and air resistance. Through calculation, the total resistance force exerted on the unmanned vessel during its navigation on the water surface is 6.53 N. To ensure the normal navigation of the unmanned vessel, the power supply power should be 5 to 6 times higher than the power required for acceleration. Since the propulsive force is provided by two propellers operating simultaneously, the power of the selected propellers should be greater than 40 W. When the vessel is sailing, the thrust provided by the thrusters should exceed the acceleration thrust, so the thrust of the selected thrusters should be greater than 5 N. To meet the endurance requirements, two polymer power lithium batteries with an output voltage of 12 V and a capacity of 12 Ah are adopted.

2.3 Unmanned Vessel Control System.

In the hardware architecture of the unmanned vessel control system, the Pixhawk 2.4.8 flight controller serves as the core processing unit, which integrates an IMU inertial measurement unit and an accelerometer to real-time sense and calculate the navigation states of the hull such as attitude and acceleration. Through its abundant external interfaces, the Pixhawk 2.4.8 flight controller connects and coordinates all peripheral devices: the GPS module provides precise latitude and longitude positioning information; the electronic speed controller receives the PWM signals output by the flight controller after PID operation to drive the thrusters and realize speed and course control; the camera establishes a connection with the remote controller via the flight controller for real-time observation of the water surface environment. Through the highly integrated scheduling of the flight controller, the entire hardware system jointly accomplishes the autonomous navigation, control and mission execution of the unmanned vessel.

3. Research on Path Planning of Unmanned Vessels

3.1 Current Research Status of Path Planning

As a core technology for the intelligent operation of unmanned vessels, path planning directly affects the quality and efficiency of unmanned vessel cleaning tasks. A scientific and rational path planning scheme enables unmanned vessels to cover the target area in small water bodies with the shortest path and minimum time, avoids repeated routes and missed areas, and achieves high efficiency and precision in garbage cleaning. Research on the design and path planning of garbage recovery vessels for floating debris on the surface of small water bodies holds important practical significance and application value for improving the ecological environment of urban small water bodies and promoting the development of intelligent environmental protection equipment.

3.2 Area Full-Coverage Path Planning

Area full-coverage path planning requires the robot to achieve a dead-angle-free traversal within a designated area, with its core objective being to minimize the path repetition rate on the premise of ensuring obstacle avoidance. To guarantee the systematicness of traversal, the depth-first search algorithm is thus considered for introduction to enhance the order and integrity of global planning.Such planning methods can be categorized into two types: the "offline" approach is applicable to scenarios with known environmental information, while the "online" approach is suitable for environments that are unknown or partially unknown, which requires environmental perception and real-time feedback through onboard sensors.Typical offline coverage strategies include the back-and-forth (boustrophedon) and spiral traversal patterns: the former achieves coverage through straight-line movement and boundary turning, whereas the latter covers the area via spiral paths, where the inner spiral contracts inward from the boundary and the outer spiral expands outward from the center. The path diagrams of the two modes are shown in Fig. 2.

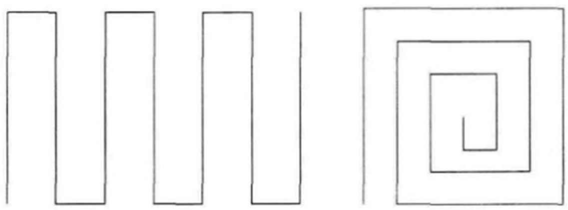

Fig. 2 full coverage path planning method

As a classic traversal and search algorithm, the core mechanism of Depth-First Search (DFS) is to explore each branch path as deeply as possible, that is, to prioritize accessing the unvisited adjacent nodes of the last arrived node [6]. In this paper, DFS is combined with the improved artificial potential field method, where DFS is applied to achieve systematic global traversal, making up for the deficiency of the artificial potential field method in the order of overall path coverage.The basic execution flow of Depth-First Search (DFS) is as follows:

Step 1: Start from the initial node G and mark it as the currently visited node.

Step 2: Traverse the adjacent nodes of the current node. If an unvisited node is found, mark it as the current node and continue the search in depth. If all adjacent nodes have been visited, backtrack to the previous node and repeat this step.

Step 3: The algorithm terminates when all reachable nodes starting from the initial node have been visited. A schematic diagram of the traversal order of this algorithm is shown in Fig. 3.

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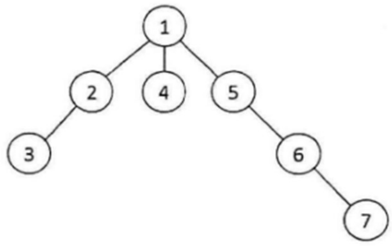

Fig. 3 algorithm traversal sequence diagram

In area full-coverage path planning, different traversal strategies exert a significant impact on the path repetition rate and coverage efficiency. To achieve full map traversal while effectively reducing the path repetition rate and improving the area coverage rate, it is necessary to select a matching coverage method. All feasible paths connected to the starting node G are systematically accessed via the depth-first search algorithm, thereby realizing global coverage.

3.3 Simulation Results and Analysis

To verify the actual performance of the area full-coverage path planning method constructed based on the depth-first traversal algorithm, simulation experiments were conducted in this study on the basis of the established grid environment model. In the simulation environment, black grids represent obstacle areas and white grids represent passable areas. The paths covered for the first time in the planning process are marked with red lines, and the repeatedly covered areas are identified with green. The simulation results are shown in Fig. 4.

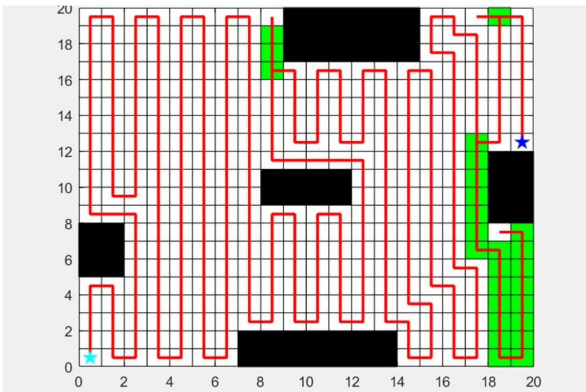

Fig. 4 area full coverage path planning simulation results

Analysis of the path planning results shows that, for the verification of the comprehensive performance of the depth-first search algorithm, the simulation experiments demonstrate that the unmanned vessel achieves a complete traversal from the start point to the end point in the environment, with the area coverage rate reaching 95%. During navigation, when reaching the boundary or encountering an obstacle (the black area in the figure), the system can automatically steer to avoid the obstruction and resume linear navigation after steering, effectively preventing local stagnation[7]. The path repetition rate is calculated as the ratio of the number of repeated grids to the total number of obstacle-free grids, and the green area in the figure represents the repeatedly covered part. The experimental results indicate that this index meets the performance requirements.

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4. Experimental Verification and Result Analysis

4.1 Construction of the Experimental Platform

The water launch verification experiment of the waste collection unmanned vessel was conducted at a certain reservoir. This reservoir features a moderate water area, relatively calm water surface and minimal environmental interference from the surrounding area, making it an ideal site for the unmanned vessel's navigation experiments. The specific reservoir environment and its corresponding satellite map are shown in Fig. 5.


Fig. 5 Experimental water area and its map

A physical prototype of the unmanned vessel for this system is shown in Fig. 6. The main structure of the unmanned vessel is a catamaran assembled by connecting two monohulls (0.7×0.2×0.26 m each) with two linking rods at the bow and stern. The main control cabinet of the unmanned vessel is fixed above the linking rods, housing a Pixhawk flight controller, a wireless data transmission module, a remote control receiver, a GPS sensor and a binocular camera, all powered by a dedicated 24V battery. The electronic speed control module inside the cabinet is connected to the propellers under the hull via wires routed through pre-drilled holes. A 30 cm gap is reserved between the two monohulls in the design, facilitating the collection of floating water surface waste by the trawl net at the stern during navigation.

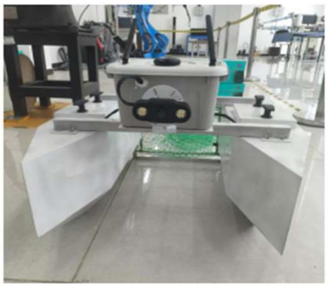


Fig. 6 The physical diagram of unmanned ship prototype

4.2 Experimental Design

The experiment relied on the Mission Planner ground station and MATLAB analysis tools, and verified the full-coverage path execution accuracy of the unmanned vessel in enclosed waters through the process of "area demarcation - trajectory presetting - physical vessel navigation - data verification".

To ensure the efficiency and completeness of full-coverage operations,a back-and-forth full-coverage path was employed as the preset trajectory in this experiment, which was generated through the "Area Coverage Path Planning" function integrated in the ground station. The visualization of the generated preset trajectory on the ground station is illustrated in Fig. 7. Overall, the trajectory exhibits a regular zigzag pattern, covering the entire rectangular operational area without obvious path intersections or uncovered regions.

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Fig. 7 Full coverage preset trajectory diagram

4.3 Simulation Results and Analysis

After the experiment, the raw data collected by the ground station was imported into MATLAB, and the Mapping Toolbox was used for data processing and visual analysis. The collected data was collated and plotted into charts via MATLAB, yielding the actual navigation trajectory of the unmanned vessel as illustrated in Fig. 8. A comparative analysis with the preset trajectory shows that there is no trajectory omission or repeated coverage within the rectangular operational area, and the actual navigation trajectory of the unmanned vessel has a high overall coincidence with the preset full-coverage trajectory. The deviations observed during navigation are mainly attributed to the instantaneous disturbances to the hull caused by mild wind and waves in the reservoir and the slight effects of water currents. The deviation range meets the accuracy requirements of waste cleaning operations in small water areas and can effectively avoid omissions or repetitions in the operational area.

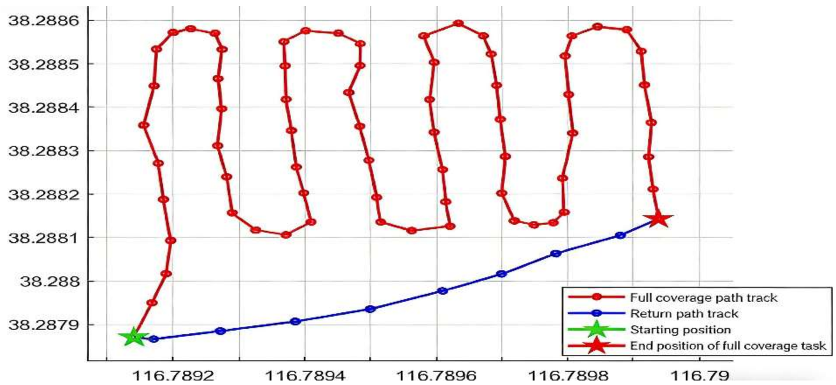

Fig. 8 Full coverage path planning actual navigation trajectory diagram

5. Conclusion

Focusing on the pollution caused by floating debris in small water areas, this paper systematically conducts research on the design and path planning of a small catamaran unmanned vessel for floating waste cleanup, which is suitable for enclosed water areas such as urban parks and landscape lakes, and completes the prototype construction as well as field experimental verification.

From system design and path planning to experimental verification, this paper forms a complete solution for the unmanned vessel used in floating waste cleanup in small water areas, which possesses certain theoretical value and practical significance, and provides a feasible technical approach and equipment support for the ecological governance of urban water areas.

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