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Path Planning under the Hull Bottom of Painting Robot Based on Heuristic Multi-robot Cooperation in Ship Manufacturing

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In the whole world, the economic loss caused by hull corrosion is enormous. Ship painting has become an important part of ship manufacturing process because it can effectively alleviate the corrosion of ship. The manual painting has disadvantages both in the quality and the efficiency. However, the research of automatic sprayers for a ship hull is not widely used because of the complex environment in the shipyard dock and the huge differences in both size and shape of ships to be repaired. Therefore, this paper proposed a new method: according to the ship size and blocks distribution in the blocks' layout of ship yards, the grid method was used to generate the map model; to solve the problems of high rerouting rate, low coverage and large consumption of calculation in the global path planning, a regional division method was proposed to divide the whole area; to shorten the dock occupancy time, a path planning algorithm based on multi robots heuristic cooperation was proposed. Simulation results and experimental data show that the full coverage path planning algorithm proposed in this paper has satisfactory adaptability.

Keywords: Spraying robot for hull bottom, Area coverage path planning, Regional decomposition, Multi robots heuristic cooperation, Grid method

1 Introduction

At present, the global merchant fleet has reached more than 100,000 ships. The adhesion of marine organisms to the hull causes steel plates corrosion, increasing sailing resistance and materials damage. The annual economic loss caused by these problems even exceeds natural disasters. This makes painting play a vital role in the shipbuilding process, and run through the whole cycle of the ship from production to use [1]. A few years ago, paints used on ships were based on toxic chemicals which could inhibit marine attaching organisms; without doubt, the ocean is seriously polluted in this way. In order to protect the ocean environment, the International Maritime Organization (IMO) requires ships to use self-shedding and non-toxic paint. However, this has caused ships to have to dock and be repainted within a certain period because of paint shedding. For instance, The RULES FOR CLASSIFICATION OF SEA-GOING STEEL SHIPS in China stipulates that ships must undergo a mandatory inspection every 30 months. At that time, the ship that is inspected must complete the cleaning of shell and subsequent repainting work in the ship-repairing yard. Generally, there are only one or two docks in large ship-repairing yards, and a shipyard need to repair 200 to 250 ships on average every year, which makes the construction period of docks very li-

mited, and it is difficult to supply the demand by manual painting. In the field of shipbuilding engineering, the efficient automatic spraying robot applied on ships has attracted more and more researchers' attention. Spraying robot has been widely used in the automobile, furniture and other industries due to its characteristics of high spraying quality, satisfactory efficiency and low requirement for working environment. However, due to the great differences in structure, size, shape and other aspects of different ships, it is difficult to realize the spraying mechanization and automation. The path planning of paint spraying robot plays a vital role in ship manufacturing technology.

The path planning methods for painting robots can be divided into two kinds: manual teaching method and offline programming method. The first one means that experienced workers plotted the spraying track on the surface, then the robot painted the area along the track. The second one means the robot planed the spraying route by itself through a path planning algorithm. The core technology in the off-line programming method is area coverage path planning (ACPP). The ACPP needs to solve the following four problems :(1) avoiding obstacles independently (for each robot); (2) reduce useless walking; (3) reduce repetitive painting; (4) reduce turning. Compared with other robots using coverage path planning methods, for instance, floor mopping robot, spraying robot for automobile, mine-disposing robot and so on. The

path planning algorithm for ship bottom spraying robot have more optimization objectives owning to its high demands on both painting thickness and obstacle avoidance. Meanwhile, the bottom area of the ship is large, and it takes a lot of time for a robot to complete the spraying operation. To solve this problem in shipbuilding enginneering, this paper proposes a heuristic multi-robot cooperative path planning algorithm, which improves the intelligence and spraying efficiency of multi-robot during cooperative operation. In ACPP algorithm, path planning on the whole ship bottom at one time causes more calculation consumption, reduces the coverage, and increases the repetitive painting, which is the reason the regional decomposition method (RDM) was created. The RDM divides the whole complex task area into several simple sub-regions to traverse successively, which greatly reduces the difficulty of path planning. However, the RDM still has some problems, such as large amount of calculation when in complex environment and immature connection technology. The process of full coverage path planning in a large known complex environment is usually divided into three steps: regional decomposition, sub-region coverage, and connection between sub-regions. The regional decomposition method mainly includes the template approach method (TAM) [2] and the cellular decomposition method (CDM) [3]. Template approach method (TAM) uses the existing path template to match the free region in the known environment to complete the traversal task in the region. However, this method is only suitable for a static environment and cannot adapt to a changing environment. The CDM includes the trapezoidal decomposition method (TDM) [4], the boustrophedon cellular decomposition method (BCDM) [5], and the Morse decomposition method (MDM) [6]. By dividing the whole complex environment into several simple regions to complete traversal respectively, the difficulty of path planning is reduced, which is suitable for path planning in a large known environment. Amna Khan proposed a new "rectangular decomposition method (RDM)" to decompose the target region [7]. In addition, the "maximize minimize angle" strategy is introduced to optimize the classical polygon segmentation algorithm [8]. Tuong Nguyen Van proposed a free-form surface partition calculation method based on MATLAB, which can divide the free-form surface into convex, concave and saddle regions [9]. When it comes to the feature of the traversal path in the sub-region, there are two kinds, reciprocating path, and internal spiral path. However, the internal spiral path is more difficult to be planned, and the breakpoints are easy to appear at the corner, so it is not widely used. The connection between sub-regions should consider the location relationship among sub-regions, spraying robots and obstacles at the same time, ensure that each sub-regions can complete collision-free connection

and reduce both the length of the repetitive walking path and the turning times as much as possible. Some researchers combine the velocity obstacle (VO) algorithm with the improved artificial potential field (APF) method to propose a two-level dynamic obstacle avoidance algorithm [10]. In order to eliminate the horizontal and vertical observation errors of obstacles, a bidirectional adaptive filtering algorithm based on polynomial fitting and particle swarm optimization is proposed [11]. In recent three years, a path tracking method based on swarm control strategy and a multi UAVs cooperative tracking strategy in the complex marine environments has been proposed to solve the path planning problem of multi-robot cooperation in a complex environment [12, 13, 14, 15, 16]. According to the traveling salesman problem(TSP), the model of the full coverage path optimization process is established and solved by genetic algorithm and ant colony algorithm [17]. To solve the local minimum and the goal non-reachable with obstacles nearby (GNRON) problems, an improved potential function is proposed for robot path planning [18]. In order to reduce the computation time, a new hierarchical path planning algorithm based on D * algorithm is proposed [19]. A route planning method for autonomous underwater vehicles based on the hybrid of particle swarm optimization (PSO) algorithm and radial basis function was proposed to prevent the improved PSO algorithm from falling into local optimum [20]. Combined with Dijkstra depth-first search algorithm, the priority-based speed control strategy is used to solve the model, and the conflict-free AGV path planning is realized [21]. A new model based on graph theory is proposed to dynamically plan the optimal path for a robot [22]. In order to solve the difficulty of a single AUV executing full coverage task on large water, the multi-AUV full coverage discrete and centralized programming is proposed based on Glasius Bio-inspired Neural Network (GBNN) algorithm [23]. Although the above algorithms can achieve full coverage in the region, they still have some problems, such as lots of repeated walking paths, poor adaptability to complex and changeable environments and so on, so they are not suitable for the path planning of painting robots under the hull bottom.

Hull's bottom is a large outdoor complex environment, so spraying the entire hull bottom with one robot consumes too much time and affects the whole schedule of ship building and ship repairing. Due to the great differences in the shape of different ships and the high requirements for paint film thickness and uniformity of spraying, at present, the painting process has not been automated in the field of ships. However, the efficiency of manual painting is low, and it is difficult to ensure the need of ship painting. To accelerate the painting speed and improve production efficiency, a heuristic multi-robot cooperative path

planning algorithm is proposed, which uses multiple painting robots to spray the hull bottom to improve the painting efficiency. Firstly, according to the particularity of the block environment under the ship bottom, a new regional decomposition strategy is proposed. The regions are divided by the extension lines of the obstacles' boundary and then remerged. The complex obstacle environment can be divided into several simple sub-regions to reduce the complexity of the solution procedure. Then, the cost function and incentive function are introduced to deal with sub-regions connection when multi robots cooperate, which ensures the painting's full coverage and makes the painting area of each robot approximately equal to enhance the advantages of multi-robot cooperation. Finally, simulation and experiments are carried out to verify the effectiveness of the algorithm.

2 Environment map model and basic assumptions

In the process of environmental map decomposition and painting path planning, the map model is established according to the real layout of blocks to ensure that the designed algorithm can achieve the effect of numerical simulation in the real dock environment. A simplified map model can accelerate the simulation speed of painting path planning, but a too simple map model will weaken the accuracy of the simulation results. Therefore, establishing an accurate map model is an essential step in path planning. Figure 1 shows the real environment of blocks under the hull bottom. It can be seen that the environment is complex. In addition to a large number of blocks, there may be other unknown obstacles such as equipments which were left out under the hull bottom after construction. According to the above situation, some assumptions are made to the environment as follows:

- It is assumed that the layout of the blocks is correct according to the blocks' layout map and the global environment is known.

- It is assumed that the shape of all blocks is the same rectangle.

- It is assumed that the environment is complex, which means there are both known obstacles and unknown obstacles.

Based on the above assumption, the blocks environment under the hull's bottom can be expressed as:

$$\Omega = \{B_k, B_u, S\}, \tag{1}$$

Where:

Ω…The blocks environment under the hull's bottom,

B_k…The known obstacles,

B_u…The unknown obstacles,

S…The free area.

$$B_k = \{B_{k1}, B_{k2}, \cdots, B_{km}\}, \tag{2}$$

Where:

m…The number of all known obstacles.

$$B_u = \{B_{u1}, B_{u2}, \cdots, B_{un}\}, \tag{3}$$

Where:

n…The number of the unknown obstacles.

For any point $(x, y) \in \Omega$ in the blocks environment under the hull bottom satisfies:

$$X_{min} < x < X_{max}, \tag{4}$$
$$Y_{min} < y < Y_{max}, \tag{5}$$

Where:

$X_{min}, X_{max}, Y_{min}, Y_{max}$…Four boundaries of the two-dimensional map model.

Fig. 1 *The blocks environment under the hull bottom*

Modeling by grid method is easy to implement and has the characteristics of consistency and standardization. The complex three-dimensional blocks environment is transformed into a simple two-dimensional grid map, and the status information of the location is stored in each grid. In this paper, the map model will be established based on the real blocks' layout map under the hull bottom. Blocks' layout map of a 70000DWT semi-submerged ship's stern is shown in Figure 2.
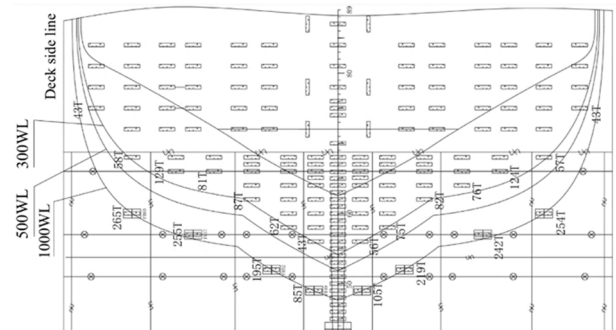
Fig. 2 *Blocks' layout map of a 70000DWT semi-submerged ship's stern*

As shown in Figure 3, the outline of the ship is cut at the height of 300mm waterline (WL), 500mm WL,

and 1000mm WL. The outline is projected to the floor, and the congruent rectangle is used to mark the position of the blocks in the drawing to get the blocks' layout map. The map model established from the blocks' layout map with grid method is shown in Figure 4.
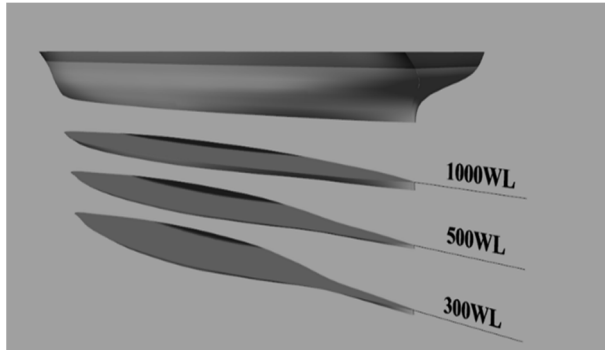

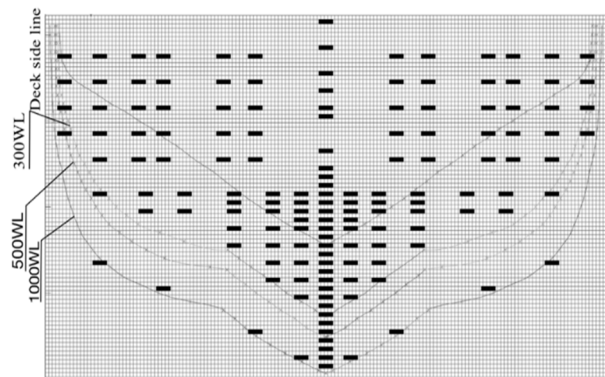***Fig. 3*** *Different waterline sections of the ship*

Fig. 4 *Grid map model*

3 Multi-robot collaborative area coverage path planning

In this paper, the full coverage path planning is divided into three steps: region decomposition, sub-region coverage, and connection between sub-regions. The specific process is shown in Figure 5.
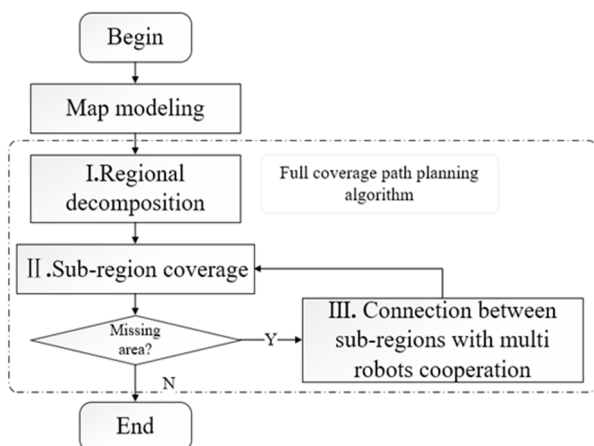

Fig. 5 *ACPP flow chart*

3.1 Regional decomposition

At present, scholars have done a lot of research on cellular decomposition method, which has a good performance in the general environment. However, most of the obstacles in the general environment have no definite shape. Considering the condition that the known obstacles in the blocks environment under the ship bottom are the same rectangle, and the blocks are generally aligned. A new region sharding scheme is proposed, which is divided into two steps: regional decomposition and regional merging. The flow chart of the scheme is shown in Figure 6.
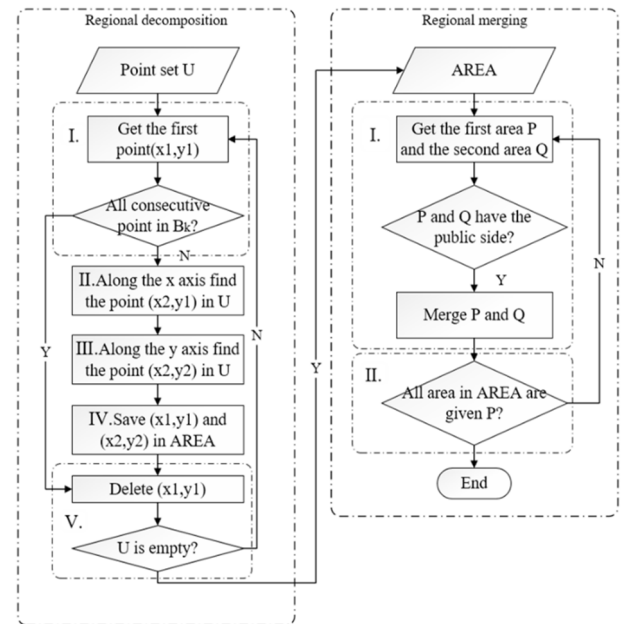

Fig. 6 *Flow chart of sharding scheme*

Table 1 shows the specific sharding scheme steps, which are described in conjunction with Figure 7.
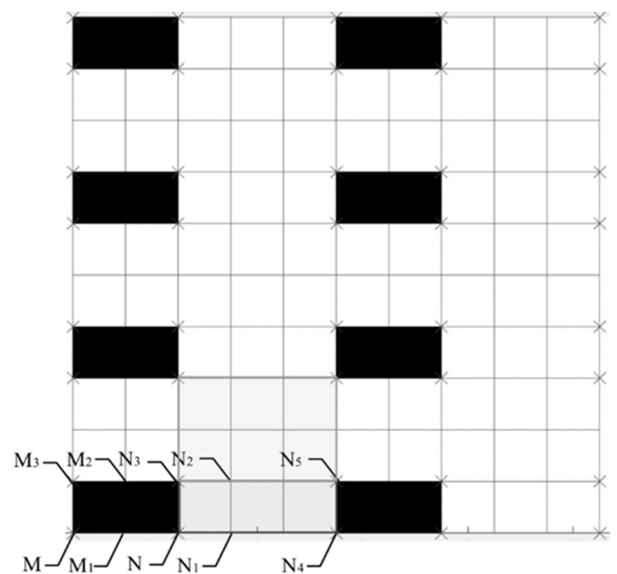

Fig. 7 *Illustration of region decomposition*

Tab. 1 *Procedure of regional decomposition*

Step		Content	Example
Regional decom-po-sition	input	The point set U of the intersection between the extension lines of the obstacle boundary and other extension lines of obstacles or map boundary	All red '×' points in Figure 7 constitute U
	I	Take the first point (x_1, y_1) from U and judge whether (x_1+1, y_1), (x_1, y_1+1), (x_1+1, y_1+1) are all in B_k. Yes, to step Ⅴ; No, to step Ⅱ	Points M and N are in U. Points M_1, M_2, M_3 are all in B_k, go to step Ⅴ. Points N_1, N_2 are not in B_k, go to Step Ⅱ
	Ⅱ	Judge whether (x_1+1, y_1) is in U. If not, continue to judge (x_1+2, y_1) until the point (x_2, y_1) is found in U	From N along X direction find N_4 in U
	Ⅲ	Judge whether (x_2, y_1+1) is in U. If not, continue to judge (x_2, y_1+2) until the point (x_2, y_1) is found in U	From N_4 along X direction Find N_5 in U
	Ⅳ	Save (x_1, y_1) and (x_2, y_2) to an array named AREA. The region between these two points is a rectangular sub-region without obstacles	The red region between point N and point N_5 is a sub-region
	Ⅴ	Delete (x_1, y_1) from U. Judge if U is empty. No, to step Ⅰ; yes, algorithm ends, output AREA	Delete points M and N. U is not empty. Go to step Ⅰ
Regional merging	Input	Array AREA	
	I	Take out the first sub-region P and the second sub-region Q from AREA, judge whether P and Q have common edges. Yes, merge the two sub-regions; No, go to step Ⅱ	In Figure 7, the red region and the green region have a common edge, indicating that the two sub-regions can be merged
	Ⅱ	Judge whether all sub-regions in AREA are assigned to P. No, take out the next sub-region and assign it to P and go to step Ⅰ. Yes, algorithm ends	

During the process of regional decomposition, the point set U of the intersections between all obstacle boundary extension lines, and the intersections between the obstacle boundary extension lines and boundary of the map is obtained through the formula (6).

$$U = U_B \cap U_P, \qquad (6)$$

Where:

U_B…The set of intersection points of extension lines of obstacle boundary,

U_P…The set of intersection points between the extension line of the obstacle boundary and the map boundary.

U_B and U_P are obtained by follows.

$$\begin{cases} U_{Bi}^j = L_i \cup L_j \\ U_B = U_1^2 \cap U_1^3 \cap \cdots \cap U_1^n \cap U_2^3 \cap \cdots \cap U_{n-1}^n \\ U_P = (L_1 \cup L_P) \cap (L_2 \cup L_P) \cap \cdots \cap (L_n \cup L_P) \end{cases} , \forall i,j \in 1,2,\cdots,n \qquad (7)$$

Where:

U_{Bi}^j…The intersection of the ith obstacle and the jth obstacle boundary extension lines,

L_i…The extension line of the ith obstacle boundary,

L_P…The boundary of the map.

This method is used to divide the map model of a blocks environment under the ship hull, and the results are given in Figure 8. Figure 8(a) shows the results of regional decomposition, and Figure 8(b) shows the results of regional merging. It can be clearly figured out that the decomposition scheme divides the entire map into several rectangular sub-regions with no obstacle and reduces the number of sub-regions through the regional merging algorithm, which decreases the difficulty of path planning and shortens the length of unnecessary paths along which robots move between the sub-regions without painting. Compared with the traditional cellular decomposition method,
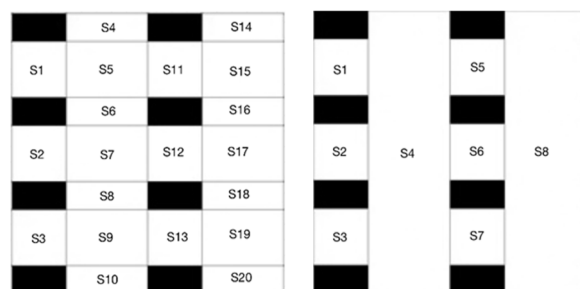
this proposed scheme is more suitable for blocks environment. And the planning result often has multiple adjacent sub-regions with the same abscissa, namely several sub-regions are in the "same column", take S1、S2 and S3 in Figure 8(b) as examples, which reduces the difficulty of connecting sub-regions in the process of multi robots collaborative planning.

(a) Regional decomposition result   *(b) Regional merging result*

Fig. 8 *The result of regional decomposition*

The result of regional decomposition satisfies the formula (8):

$$\begin{cases} S_1 \cup S_2 \cup \cdots \cup S_n = S \\ S_i \cap S_j = \emptyset \quad , \forall\, i,j \in 1,2,\cdots,n, i \neq j \\ S_i \text{ is a rectangular region } \forall\, i \in 1,2,\cdots,n \end{cases} \quad (8)$$

Where:

S_i…The ith sub-region,

n…The number of all sub-regions.

3.2 Sub-region coverage

After the region is divided into sub-regions, the robots are about to traverse each sub-regions. As shown in Figure 9. Common full coverage paths are reciprocating paths (Figure 9(a)) and internal spiral paths (Figure 9(b)). Although the internal spiral path spraying can obtain slightly higher quality paint film, its planning is more difficult, and breakpoints are easy to appear at the corners. So, it is not suitable for the large and complex environment under the hull's bottom. The reciprocating path planning is simple and can ensure the quality of paint film. It has two schemes: traversing along the long side (Figure 10(a)) and traversing along the short side (Figure 10(b)).
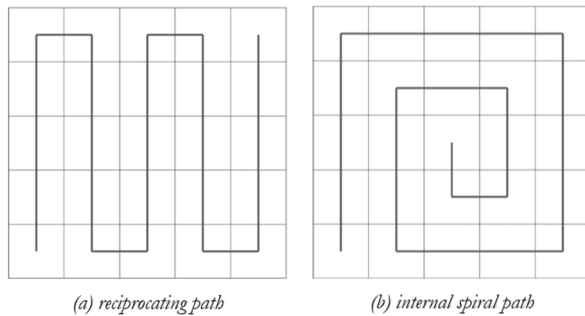

(a) reciprocating path　　　(b) internal spiral path

Fig. 9 *Two full coverage path*

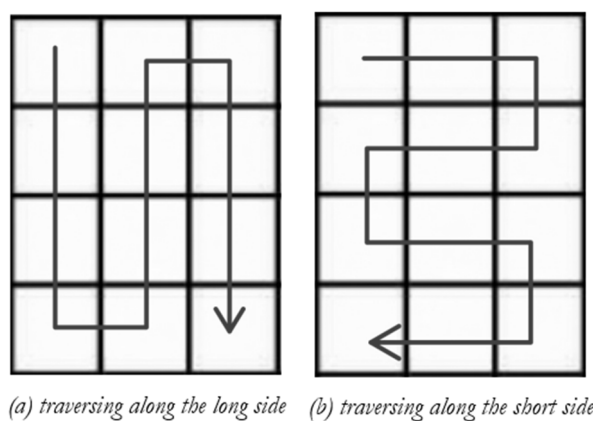(a) traversing along the long side　(b) traversing along the short side

Fig. 10 *Two reciprocating paths*

In Figure 10, the size and shape of the two sub-regions are the same. The scheme traversing along the long side has only four turnings, while the scheme traversing along the short side has six turnings. Therefore, the reciprocating path traversing along the long side is used for full coverage path planning in sub-regions.

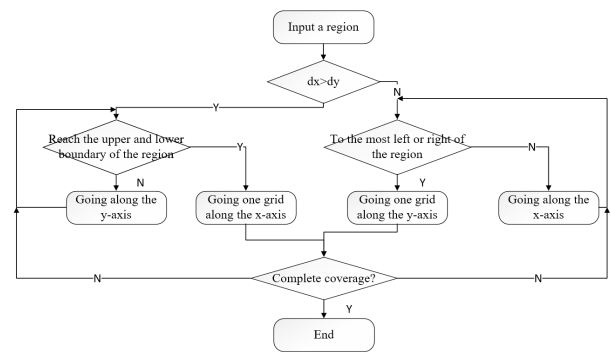The flow chart of path planning in sub-regions is shown in Figure 11.

Fig. 11 *Path planning in sub-region*

3.3 Connect between sub-regions with multi-robot cooperation

After traversing a sub-region, the spray painting robot should move from the current sub-region to the next to continue to paint. In the process of transfer between the sub-regions, two position relationships should be taken into consideration: the position relationship between the unfinished sub-regions and the sub-regions where the robots are located, and the position relationship between each spray painting robot. Moreover, the area of repetitive walking in the process of connecting the sub-regions should be as small as possible. And the spraying area of all robots should be approximately the same to maximize the effectiveness of each robot and heighten the spraying efficiency.

The map model of finished decomposition shown in Figure 8(b) is transformed into the topology diagram shown in Figure 12. The nodes in the diagram represent different sub-regions, the links represent the paths connected the sub-regions, the length of the links represents the cost of the robot moving between the two sub-regions, and each robot can move between the connected nodes. All sub-regions are divided into three types: the sub-region that the robot is traversing (S_w), the sub-region that has been traversed (S_d), and the sub-region that has not been traversed (S_g).
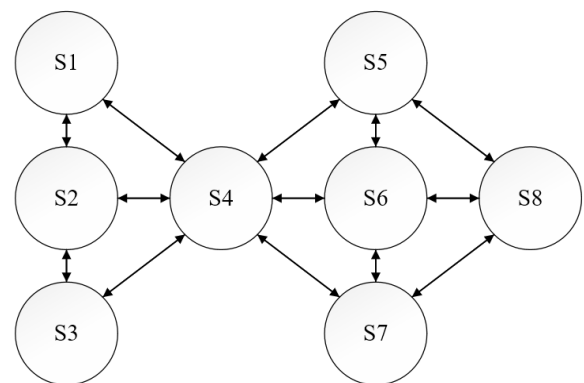

Fig. 12 *decomposition result topology diagram*

In order to make each robot moves along the shortest path between sub-regions, a cost function F is proposed to calculate the consumption of the robot when moving between sub-regions.

$$F_j = \mu \sqrt{(x_{i+1,j} - x_{i,j})^2 + (y_{i+1,j} - y_{i,j})^2} \quad (9)$$

Where:

μ…The distance weight,

F_j…The consumption of the jth robot.

As shown in Figure 13(a), if the distance consumption is the only factor considered, on the condition two robots are working in the same row of sub-regions, after the No.1 robot completes the traversal work in its sub-region, it will cross the sub-region where the No.2 robot is located and continue to traverse in S1,

which is called interleaving traversal situation. This will greatly increase the length of robots' useless walking with no painting and weaken the advantage of multi-robots cooperation. So, a cost parameter χ is introduced. The cost function becomes:

$$F_j = \mu \sqrt{(x_{i+1,j} - x_{i,j})^2 + (y_{i+1,j} - y_{i,j})^2} + \chi \quad (10)$$

When a robot is traversing in a sub-region, all sub-regions which are not traversed in this column will give an additional cost χ to other robots. After introducing the parameter χ, the result of path planning under the same condition is shown in Figure 13(b). It can be seen that the two robots can cooperate more intelligently to complete the traversal work and reduce the length of robots' unnecessary walking.
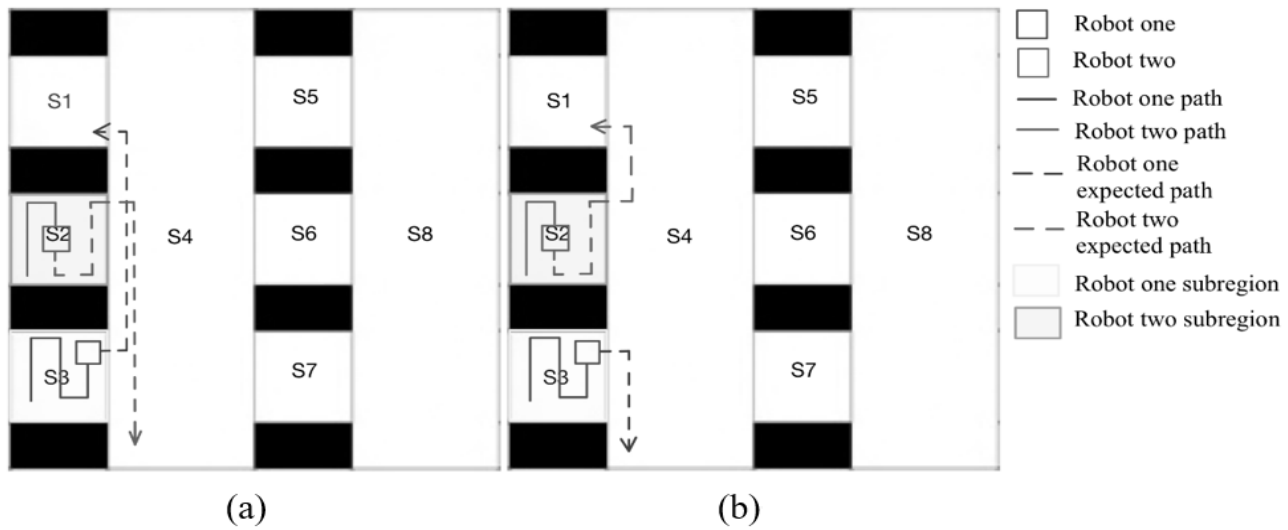

Fig. 13 *Two robots traverse in the same column of sub-regions*

Besides, to take each sub-region into account and ensure the full coverage of the planned path, an excitation function G is proposed for encouraging the robots to traverse the sub-regions in the same column firstly. Finally, the target sub-region of the jth robot is determined by the evaluation function H which is shown as follow.

$$H = -F_j + G_j \quad , \forall j \in 1,2,\cdots,m \quad (11)$$

The cost function F and the excitation function G are shown in formula (12).

$$\begin{cases} F_j = \mu \sqrt{(x_{i+1,j} - x_{i,j})^2 + (y_{i+1,j} - y_{i,j})^2} + \chi_{i+1,j} \\ G_j = \gamma_{i+1} \end{cases} , \forall i \in 1,2,\cdots,n-1, \forall j \in 1,2,\cdots,m \quad (12)$$

Where:

μ…The weight of distance on the total cost,

$\sqrt{(x_{i+1,j} - x_{i,j})^2 + (y_{i+1,j} - y_{i,j})^2}$ …The Euclidean distance from the current sub-region to the next sub-region,

i …The ith sub-region, namely the sub-region where the robot is currently located,

j…The jth spray painting robot,

χ…The additional cost parameter,

γ…The additional excitation parameter,

n…The total number of sub-regions,

m…The total number of robots.

In order to better obtain the state information of sub-regions, we saved each sub-region in a matrix E, and established the environment information database. It contains the environment information of all sub-regions, which is used for the multi-robots collaborative path planning. The data stored in E is:

$$E = \begin{bmatrix} x_{l1} & y_{l1} & x_{r1} & y_{r1} & \chi_1^1 & \gamma_1^1 & \cdots & \chi_1^m & \gamma_1^m & state_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{ln} & y_{ln} & x_{rn} & y_{rn} & \chi_n^1 & \gamma_n^1 & \cdots & \chi_n^m & \gamma_n^m & state_n \end{bmatrix} \quad (13)$$

Where:

E…Matrix of n rows and $2m + 5$ columns, each row contains the information of a sub-region,

x_l, y_l and x_r, y_r…The vertical and horizontal coordinates of the lower-left corner and the upper-right corner of the sub-region,

χ_i^j and γ_i^j…The additional cost value and excitation value of the ith sub-region for the jth robot,

$state$…The state of the sub-region, the non-traversed sub region is 0, the traversing sub-region is 1, and the traversed sub-region is 2,

$$(x_{li} = x_l^j) \wedge (x_{ri} = x_r^j) \Rightarrow \begin{cases} \chi_i^k = P \\ \gamma_i^j = Q \end{cases} , \forall i \in 1, 2, \cdots, n, \forall j, k \in 1, 2, \cdots, m, j \neq k \tag{14}$$

Where:

x_l^j and x_r^j…The abscissa of the current working sub-region boundary of the jth robot,

P…The cost parameter of the ith sub-region to the kth robot,

Q…The excitation parameter of the ith sub-region to the jth robot. The sub-regions which satisfy $(x_{li} = x_l^j) \wedge (x_{ri} = x_r^j)$ are the sub-regions in the same column as the current working sub-region of the jth robot.

After calculating the target sub-region of the spray painting robot through the evaluation function H in formula 5, the distance between the grid where the robot is located and the four vertices of the target sub-region is calculated, and the vertex with the shortest path is selected as the starting point of the full coverage path of the target sub-region. Finally, the A* algorithm is used to plan the shortest collision-free path from the current grid to the target grid, and then the sub-region traversal task is continued.

4 Simulation experiment

The simulation scheme is as follows: First, the map model shown in Figure 4 is established by using the blocks' layout map of a ship's stern in Figure 2 in Chapter 2. The stern curve is the most complex in the whole ship, so the layout of blocks is more complicated than that of the middle and bow. In the simulation, two painting robots are initialized in the free grid of the map to test the effect of their cooperative traversal. Finally, using the scheme proposed in this paper, two painting robots cover the entire map, and coverage rate and the overlapped rate of their planned path are obtained.

4.1 Simulation parameter setting

In this paper, a simulation platform is established

n and m…The total number of sub-regions and robots respectively.

After the painting robot completes the traversal in its current sub-region, it will search for the non-traversed sub-region with the largest H value in the sub-region list. To make sure that each robot searches the next target sub-region autonomously and complete the whole area traversal task intelligently and cooperatively, χ and γ of different sub-regions to different robots in matrix E are updated in real time through the following formula.

based on Matlab2019 in Windows 10 system, with 16G computer RAM and 2.5GHz CPU speed. The map model is generated by the grid method. The size of grids has a great influence on the difficulty and quality of path planning. Big grids give rise to strong anti-interference ability and less memory space but result in weak ability to find available path in the close obstacle environment. Small grids give rise to more environment information but result in weak anti-interference ability, less memory space, and slow calculation speed. In this paper, the grid size is set to equal to the width of the block, which can maximize the speed of decision-making under the premise of ensuring environmental resolution. In formula 7, the cost parameter P is set to 50, and the incentive parameter E is also set to 50. The value of $state$ is updated based on the state of the sub-region. The number of painting robots is set to 2, the size and speed of the two robots are the same. The two robots cooperate to complete the whole area traversal task.

4.2 Building simulation map model and regional decomposition

The grid map established by the grid method is shown in Figure 4, where black represents the obstacle grids and white represents the free grids. This task is to traverse the area within the baseline and use the decomposition scheme proposed in Section 3 to decompose the area within the baseline. The decomposition result is shown in Figure 14. Figure 14(a) shows the result of regional decomposition, with a total of 609 sub-regions; Figure 14(b) shows the result of regional merging, with a total of 73 sub-regions. After regional merging, the number of sub-regions is greatly reduced, the number of robots transferring between sub-regions and the repetitive path is greatly reduced, and the spraying efficiency is significantly improved.

(a) Regional decomposition results   *(b) Regional merging results*
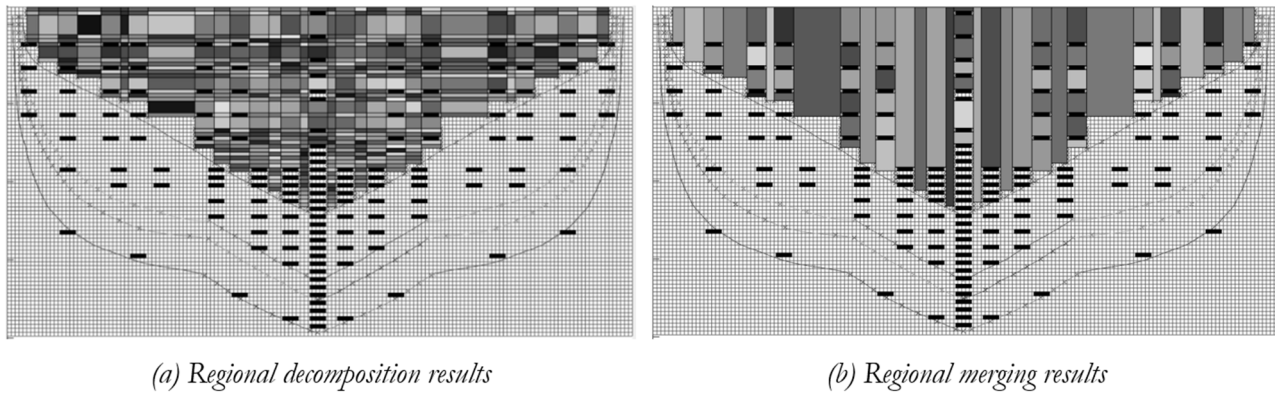
Fig. 14 *Regional decomposition within the baseline*

4.3 Traversal in sub-regions and transfer between sub-regions

After the regional decomposition, two spray painting robots are generated in the map model, and the area traversal work is carried out for the task area of each robot. To illustrate that the algorithm proposed in this paper can complete the full coverage path of multi-robot with efficient cooperation under different initial conditions, three typical situations are selected for simulation. Simulation results of three typical cases

about robots' cooperative traversal are given in Figure 15, which are robots start painting from both sides of the ship (Figure 15(a)), from the middle of the ship (Figure 15(b)), and from one side of the ship (Figure 15(c)). In the figures, the yellow area is traversed by the No. 1 painting robot, the blue area is traversed by the No. 2 spray painting robot, the red line in the yellow area is the path that No. 1 painting robot navigates, and the black line in the blue area is the path that No. 2 painting robot navigates.

(a) Example 1: Two painting robots start painting from both sides of the ship   *(b) Example 2: Two painting robots start painting from the middle of the ship*   *(c) Example 3: Two spray painting robots start painting from one side of the ship*
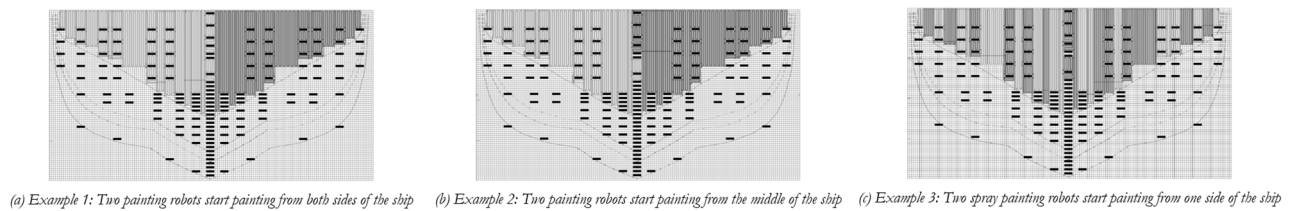
Fig. 15 *Simulation of Cooperative Path Planning for two robots in three cases*

Compared with the results of the complete coverage path planning by the method proposed in this paper and the improved ant colony algorithm, the path length, turning times, and the specific value of the path length of these two robots in three cases are

listed in Table 2. It can be seen that the path-length specific value of the two robots is close to 1:1 in each case, which proves that the multi robots cooperative path planning algorithm proposed in this paper heightens the advantages of multi-robots cooperative work.

Tab. 2 *Collaborative planning path results of two robots in three cases*

Initial position of robots		Total path length	The length of path without work	The rate of path without work	Path length ratio of two robots	ratio of coverage
Heuristic multi-ro-bots coo-perative algorithm	From both sides of the ship	4668	489	10.48%	1.043	100%
	From the middle of the ship	4662	483	10.36%	1.009	100%
	From one side of the ship	4727	548	11.59%	0.997	100%
Improved ant colony algorithm	From both sides of the ship	4898	719	14.68%	1.146	100%
	From the middle of the ship	4877	698	14.31%	1.124	100%
	From one side of the ship	4959	780	15.73%	0.901	100%

Simulation results show that the proposed heuristic multi robots cooperative area coverage path planning algorithm outperforms the improved ant colony algorithm in three typical cases. The path length of the two robots planned by the proposed algorithm is almost equal, and the rate of useless walking which navigates with no painting is limited below 10%, all indicate high painting efficiency. Among the three cases, two robots start from the middle of the ship gives the lowest rate of useless walking. The reason is that the H of the sub-regions in the middle of the ship calculated is similar, and the two robots can cooperate to complete the traversal work in the middle of the ship.

5 Field experiment

To prove that the algorithm proposed in this paper not only has good simulation results, but also makes robots cooperate to complete full coverage path planning in practical use, two painting robot prototypes are built to carry out cooperative operation experiments in a typical environment. Due to the hull is too big to build, a part of the area in the middle of the ship is intercepted for the experiment, and the size of the experimental site is 35 × 41.

The experimental robots are built based on STM32F103. To design a modular experimental car, the whole hardware is divided into motion control system, man-machine interactive system, power supply system, and locating obstacle avoidance system. The hardware design of the system is shown in Figure 16.
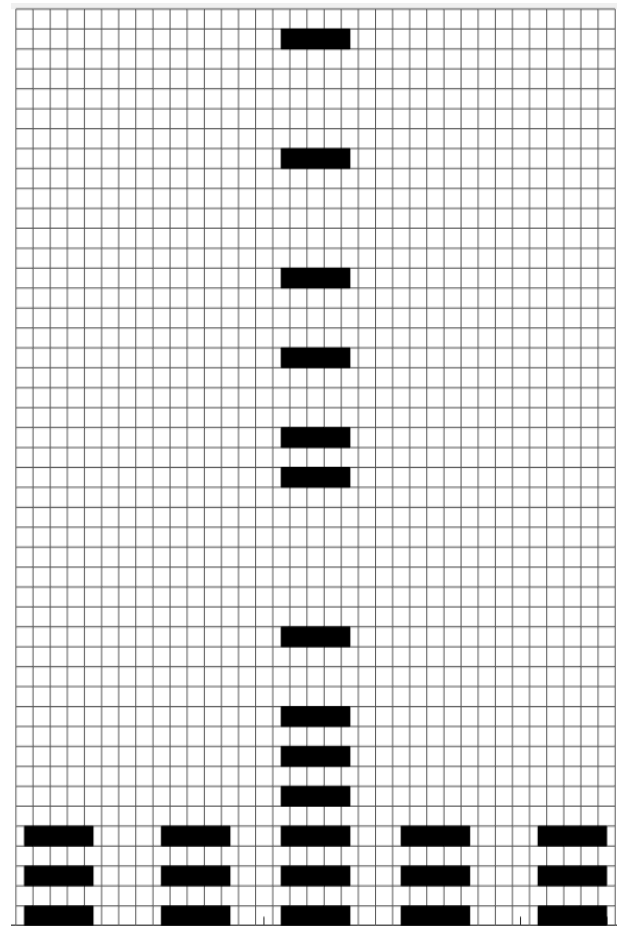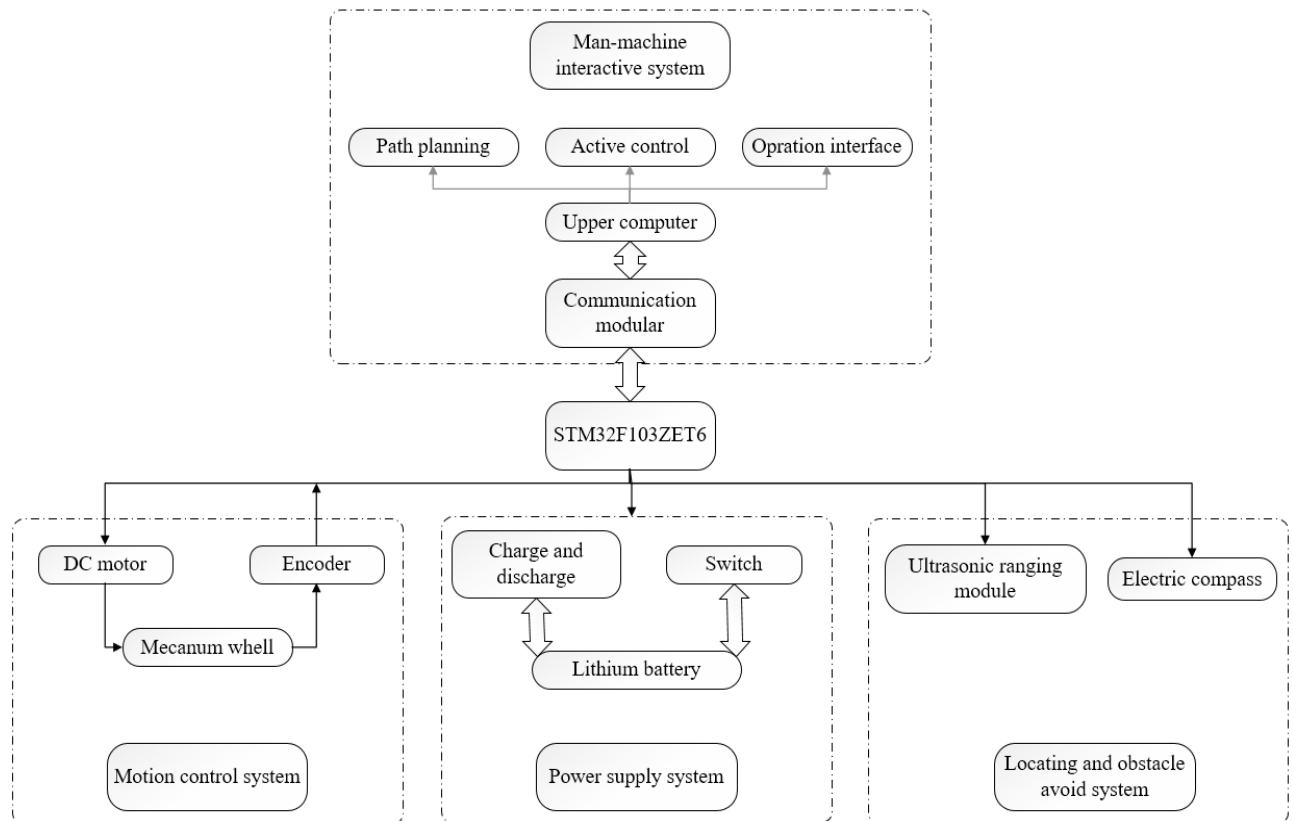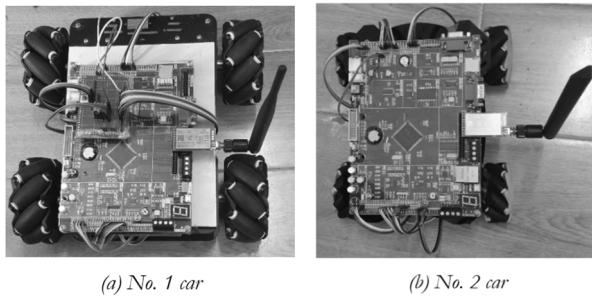

Fig. 16 *Experimental map model*

Fig. 17 *Hardware system block diagram*
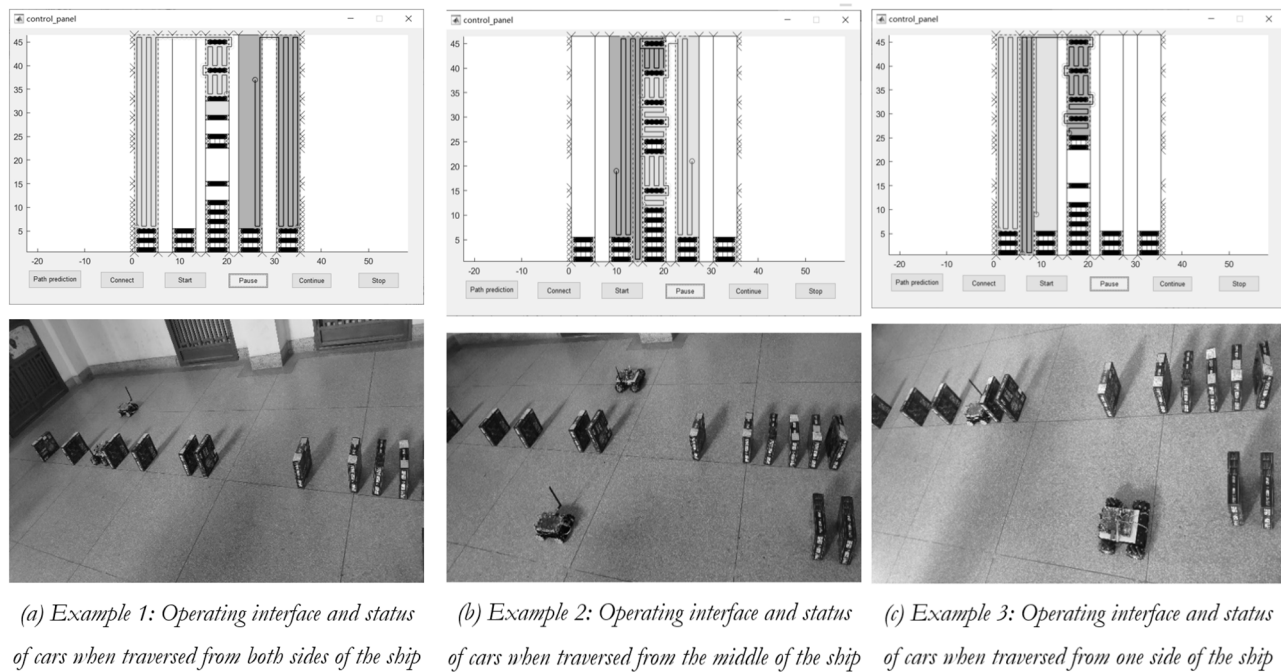
(a) No. 1 car   *(b) No. 2 car*

Fig. 18 *Experimental cars*

After completing the design of the hardware system, wiring and installing the experimental cars and writing the MCU control program, the completed car is shown in Figure 18. The No. 1 experimental car is 256mm long, 269mm wide, 133.5mm high and with 80.5mm wheels. The No. 2 experimental car is 215mm long, 188mm wide, 71mm high and with 65mm wheels. To improve the dirigibility of the experimental car, two cars are equipped with Mecanum wheels; each motor is equipped with an encoder to calculate the speed and precisely control the length of the car's

travel, and the car is equipped with an ultrasonic ranging module to prevent the car from colliding with unknown obstacles.

The upper computer operation interface is designed with MATLAB. It can preview the path, connect the slave computer, start traversing, pause and continue, terminate tasks, and display the real-time position of the experimental cars through the operation interface.

The experimental environment is arranged according to the map model shown in Figure 16 and the experiments are carried out to verify the feasibility of the proposed heuristic multi-robots cooperative area coverage path planning algorithm. The operating interface and the status of cars in three cases are shown in Figure 19. The unfinished traversal sub-regions after regional decomposition are white, and the sub-regions are separated by black lines. The yellow regions are the areas traversed by the No. 1 car, and the red line in the yellow regions is the track of the No. 1 car. The blue regions are the areas traversed by the No. 2 car, and the black line in the blue regions is the track of the No. 2 car.

(a) Example 1: Operating interface and status of cars when traversed from both sides of the ship

(b) Example 2: Operating interface and status of cars when traversed from the middle of the ship

(c) Example 3: Operating interface and status of cars when traversed from one side of the ship

Fig. 19 *Car walking experiment*

The experimental results prove that the two cars can work together to complete traversing work in the area according to the path planned by the algorithm. The coverage rate is 100% and the path length of the two cars is approximately the same. The heuristic multi robots collaborative path planning algorithm can reasonably determine the next target sub-region of the car according to the state of each car and sub-region, and fully utilize the advantages of multi robots collaboration, improve painting efficiency in practical application.

6 Conclusions

Painting robots are not widely used in shipyards. Most of the ship spraying operations are still manually sprayed by workers. But this spraying method is inferior to painting robots in terms of quality and efficiency. In this paper, a new regional decomposition method is proposed based on the particularity of blocks environment in the ship-repairing yard. The number of sub-regions is effectively reduced by using

regional decomposition and regional merging, and the useless path of painting robot in the transfer process between sub-regions is less planned. A heuristic multi-robots cooperative path planning algorithm is proposed. The target sub-regions of each robot are determined by continuously updating the cost value and incentive value of sub-regions for each robot, so that the paths of each painting robot are roughly equal, which fully utilize the advantages of multi-robots collaboration. Finally, the effectiveness of the proposed area coverage path planning algorithm is verified by simulation and experiment. The path planning algorithm for painting robot proposed in this paper promotes the painting automation in the field of ship engineering. Compared with manual spraying, automatic spraying will greatly improve the efficiency of manufacturing and production and promote the development of manufacturing technology in the field of ship engineering. However, a large-scale experimental prototype in a real environment in the dock is not tested. In the further research, when the painting robot is working in the dock, it should carry out simultaneous localization and mapping for unknown obstacles and placement errors of docks to improve the self-adaptive ability of the painting robot in a complex environment.

Acknowledgments

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