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A Compound PRM Method for Path Planning of the Tractor-Trailer Mobile Robot*

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***Abstract*-This paper researches the path planning problem for the tractor-trailer mobile robot and presents a novel environment modelling method called Compound PRM which builds the global compound roadmap by combining the local regular roadmap with the universal probabilistic roadmap. Path planning based on the Compound PRM roadmap can improve the quality of the local routes near obstacles and lower the complexity of the planning computation. Also the loss of feasible space is avoided during path planing. The simulation experiment shows that this method is very efficient in the use of tractor-trailer mobile robot path planning.**

Index Terms – Tractor-trailer mobile robot. Path planning. Roadmap. Compound PRM.

I. INTRODUCTION

The tractor-trailer mobile robot is a kind of robot system with a driven tractor dragging several passive trailers, which is promising in logistic use to carry goods to certain destinations as shown in Fig1. Path planning for this type of robot is of special importance use for its potential use as transportation tool.

Probabilistic Roadmap (PRM) method captures great interest in recent years for its simplicity and efficiency in robot motion planning [1]. An important feature of PRM is that it supports the once modeling, multi-query planning problem, which makes it quite suitable for robots working in the fixed environment. The tractor-trailer mobile robot may serve as the transport tool moving in certain fixed fields and its operation position often changes with the task it assumes. When the start and goal point changes, the path that the robot will take may be planned based on the same roadmap. So its path planning can be defined as a multi-query problem.

This paper research the path planning problem of tractor-trailer mobile robot based on PRM method. For the special feature the tractor-trailer robot possesses, the conventional PRM can't be used directly to the tractor-trailer mobile robot for excellent result. So a new model called Compound Probabilistic Roadmap (also called Compound PRM) is presented in the following content to solve the path planning problem for tractor-trailer mobile robots. A series of experiments are conducted to validate the method and check its performance in contrast to other method.

II. PRINCIPLE OF COMPOUND PRM PLANNING

A. Problem Formation

The tractor-trailer mobile robot is a nonlinear and non-holonomic system with not enough drive [2]. Due to the influence of non-holonomic constraint and the limit of the turning mechanism, the tractor-trailer mobile can't drive sideways and a minimum turning radius exists for it. The constraints can't be ignored during path planning, and otherwise a path planned may be not useable though it locates in the free configuration and suitable for a general robot. The concept of Equivalent Size is introduced in [2] which compute the maximum width (ES) the tractor-trailer robot approaches at its limit turning (written as $R_{\min}$ --the minimum turning radius the robot can make). The Equivalent Size varies with the shape, size and number of trailers of the tractor-trailer robot and can be computed for a certain tractor-tractor robot system. Then the Equivalent Size can be used into environment modeling for available planning methods, which simplify the path planning problem for this kind of robots.

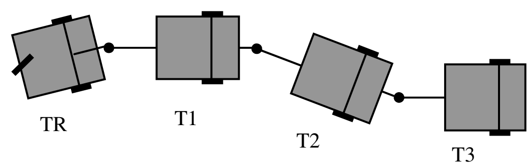

Fig1. Tractor-trailer mobile robot with three trailers

Much research work has been conducted on path planning for mobile robots. Grid method and potential method and their variants are among the most famous method used in path planning before the PRM method became popular for its computational feasibility in practice [11]. However, the known work on path planning for the non-holonomic mobile robot based on PRM used to rely on the local planner to adapt to the constrains, which inevitably results in great computing complexity and low planning efficiency . So the Compound PRM method is proposed here to apply the PRM method rightly in the path planning for the tract-trailer mobile robot.

Suppose that the tract-trailer mobile robot works in a two dimensional flat space with some stationary obstacles in it and this space is called physical space. To facilitate path planning, the physical space is mapped into a data structure called

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configuration space located in the robot memory which denotes the position and pose of the robot and the obstacles in the same environment. In the configuration space the parts not occupied by obstacles are called free space and the goal of planning is to find a path located in the free space that meets the non-holonomic constraints for the tractor-trailer robot [6]. For path planning in the configuration space, the robot is abstracted into a particle and the obstacle is enlarged according to Equivalent Size of the tractor-trailer mobile robot before certain method is used to model the environment where the robot locates.

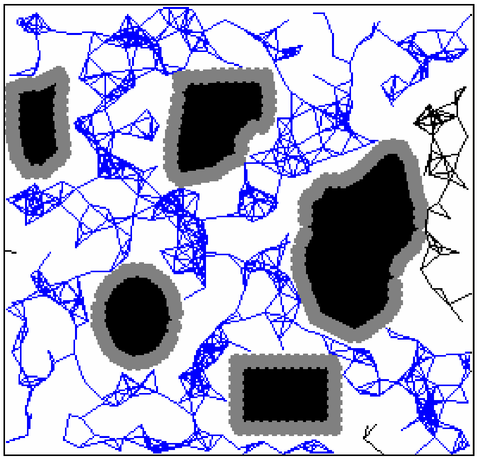

Fig.2 The PRM roadmap

B. Principle of Compound PRM Path Planning Method

As shown is Fig.2, the core mind of conventional PRM is to use a random roadmap to capture and define the connectivity of the free space [3], and then a certain graph search method is used on the roadmap to find an available path for the robot. The path is composed of a series of nodes and edges, with a node meaning a free configuration of the robot and an edge meaning an available local path between two adjacent nodes.

The environment model that PRM used is a road network build by random method [5, 7]. Robot configuration space should be randomly sampled for free configurations and local planner would connect the free configurations. If the sample is even enough so that all free spaces are covered, the connectivity of the free space will be defined well.

The PRM method works well in the area far enough from all obstacles. But in areas with complex obstacles, some problems may occur as follows. First, a route built by connecting random nodes may be so irregular that it can't be smoothed and tracked, especially for non-holonomic tractor-trailer mobile robot. Secondly, collision verification beside obstacles is so complex that the local planner' computation load is too heavy. In addition, some narrow passages may not be covered by road network due to the random sample mode.

Grid map is another environment representation model used in path planning which is not quite suitable for multi-query problem [4]. Considering the excellent performance grid map shows in modeling and path planning near obstacles, grid map is combined with PRM map in this paper to form the compound probabilistic roadmap to capture the connectivity of the free space in the whole configuration space.

The Compound PRM map for a tractor-trailer robot in certain environment is built as the following steps. On one hand, each obstacle is enclosed with rectangular network composed of grids with universal size determined by the robot's Equivalent Size. On the other hand, the conventional PRM method is used in the free area far enough from any one obstacle to build probabilistic roadmap networks. Then the two kinds of road networks-grid network and probabilistic road network- are connected to form a whole roadmap called Compound Probabilistic Roadmap. Path planning based on Compound PRM model overwhelms the defect of the PRM method near obstacles while preserves the high efficiency and learning capability of conventional PRM.

III. IMPLEMENTATION OF COMPOUND PRM PLANNING

A. Description of Compound PRM Method

Path planning based on Compound PRM fall into three steps which are preprocessing, query and path smoothing. In the preprocessing phase, Compound PRM roadmap is built as the method presented in part II. Then, path search is conducted in the query phase and as a result, a path that comprise of a series of edges can be obtained. In the third phase, the path is smoothed so that the non-holonomic tractor-trailer mobile robot can track it. The main steps of the Compound PRM algorithm are as follows:

Compound PRM ALGORITHM

I. PREPROCESSING: ROADMAP CONSTRUCTION

1.Grid Network Generation

2.Probabilistic Roadmap Generation

3.Connection of Grid Networks to Probabilistic Roadmap

II.QUERY PROCESSING

1.Connect Start Point and Goal Point to the Roadmap

2.Search the Roadmap for a Path of Connected Nodes

3.Global Path Optimalization

III.PATH SMOOTHING

1.Local Path Re-computation

2.Path Smoothing

3.Global Feasible Path Reconstruction

B. Building Local Regular Roadmap

Enclose each obstacle with a network of grids in shape of square. The length of the side of each grid is the same as the minimum turning radius $R_{\min}$ of the robot. All the grids form a rectangle surrounding the obstacle. The grid network is seen as a regular local roadmap in which an edge of each grid represents a local route and a vertex of each grid represents a node in which many routes meet. A series of regular local roadmap may be obtained by treating the obstacles one by one as above and all the local roadmaps constitute the regular roadmap set G_r .

C. Building the Probabilistic Roadmap

Initially, the random roadmap network is empty and recorded as $G_p = (V, E)$. The following operation repeatedly captures random nodes from the free configuration space and adds them into the node set V. As to each newly added node, adjacent nodes should be selected for it from the nod set V, and then the local planner try to connect the new node and its adjacent nodes in a certain scope which are also called neighbour nodes. If the local planner confirms that an available route exists between the node q and its neighbour q', a new edge (q, q') should be added into the roadmap and recorded in edge set E. Above operation will continue until the size of the node set reaches the preset value and then a probabilistic roadmap composed of nodes and edges comes into being as in Fig.2. The algorithm to generate the probabilistic roadmap adopted here is the same as defined in [3].

Before building the probabilistic roadmap, several key details should be considered.

First is to choose the way that the free configuration is sampled which denotes how to distribute the nodes in the free space. The rule is that the sample algorithm should try to cover all free space so that the connectivity of work space of the robot can be reflected comprehensively.

To increase the sample efficiency, a two-step sample method is adopted in this paper. Suppose that the number of the total nodes is N, μN nodes are generated in the wholly probabilistic way in the first step. Note that the parameter μ is less than 1. Then in the next step, other $(1-\mu)N$ nodes are generated in a heuristic way to assure that these nodes are necessary to cover the remainder free space ignored in the first sample step. The parameter μ can be adjusted according to the experiment result to approach an optimal value.

Second is to decide the type of the local planner whose role is to plan a local path between two nodes. The local planner has many options and each option may have its own success case. To increase the efficiency of the preprocessing phase, the simplest linear local planner is adopted. At first, the linear local planner builds a linear route between two nodes, and then the collision detection is conducted on the route to avoid obstacles.

The third problem is how to identify neighbour nodes. During building the PRM roadmap, a set of neighbor nodes should be selected for each new node added into the node set V. A range standard for neighbor nodes should be established to filter the surrounding nodes.

In this paper, the distance between two nodes m and n is defined as below:

$$D(m,n) = Len(P_l(m,n)) \qquad (1)$$

Here, $Len(P_l(m,n))$ refers to the Euclidean linear distance between m and n since the local planner is linear.

The range standard for qualifying neighbor node set of node q is:

$$N_q = \left\{ q' \mid q' \in V, \min dist \le D(q, q') \le \max dist \right\} \qquad (2)$$

The above expression show that each node in the neighbor set of q should fall into a circular region which is farther than the upper limit $\max dist$, but closer than the lower limit $\min dist$. The parameter $\max dist$ is set to assure that the neighbour nodes is close to q enough, while the parameter $\min dist$ is set to assure that the subsequent path built based on the PRM roadmap can be smoothed for the non-holonomic tractor-trailer mobile robot.

D. Building Compound PRM RoadMap

Merge the regular roadmap and the probabilistic roadmap by connecting certain key nodes on both roadmap borders with the local path planner. Then a comprehensive and compound roadmap that describes the connectivity of the whole free configuration is obtained as seen in Fig.3 and it is just the Compound PRM roadmap.

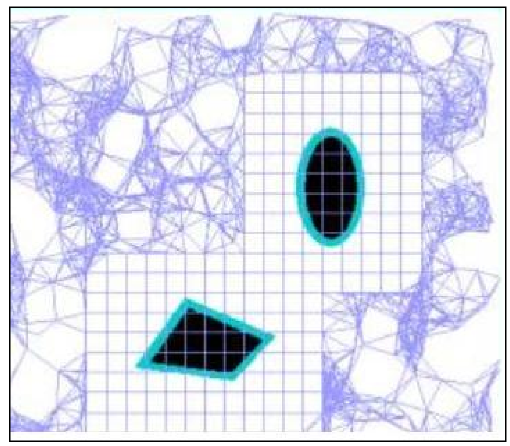

Fig.3 Compound PRM roadmap

E. Path Search

Given the start configuration q_{start} of the mobile robot and the goal configuration q_{goal}, path planning may be solved base on the Compound PRM roadmap built before. First a local planner will connect respectively q_{start} and q_{goal} to q'_{start} and q'_{goal} on the Compound PRM roadmap through local route P_{start} and P_{goal}. Then a graph search algorithm is used to find a shortest path P_c between q'_{start} and q'_{goal}. The final global path connecting the start and goal configuration comprises of three parts: P_{start}, P_{goal} and P_c.

Note that during the path search process, the Compound PRM roadmap should be treated as a single map no matter which type of roadmap is under search. Many graph search algorithms can be used for path search based on the Compound PRM roadmap to find an optimal path. Dijkstra Algorithm is used in this paper to assure that an optimal path can be found.

Dijkstra Algorithm assures that the road found is the shortest between the initial point and goal point. In addition, the path from the initial point to any middle point is the shortest, as shown in Fig.4. Suppose that node v_1 and v_3 can be connected by across two different nodes v_5 or v_2 , the Dijkstra Algorithm must select v_2 as the middle point. Thus the former search result between some key positions can be stored for later use as the optimal feature can be preserved, which is especially suitable for transport robot use.

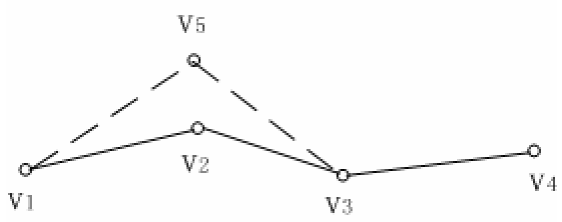

Fig.4 Dijkstra algorithm

F. *Path Smoothing*

The path obtained based on Compound PRM is composed of a series of linear route and many cross points exist on the path. So the non-holonomic tractor-trailer mobile robot can't track the originally planned path unless the angles on the path are smoothed.

In fact, the feasible path that a tractor-trailer robot can track is composed of a series of arcs and lines. An arc should be adopted to bridge any two adjacent lines and meet the following condition:

$$r_{arc} \le R_{\min}$$

Where r_{arc} is the radius of the arc while $R_{\min}$ is minimum turning radius of the mobile robot.

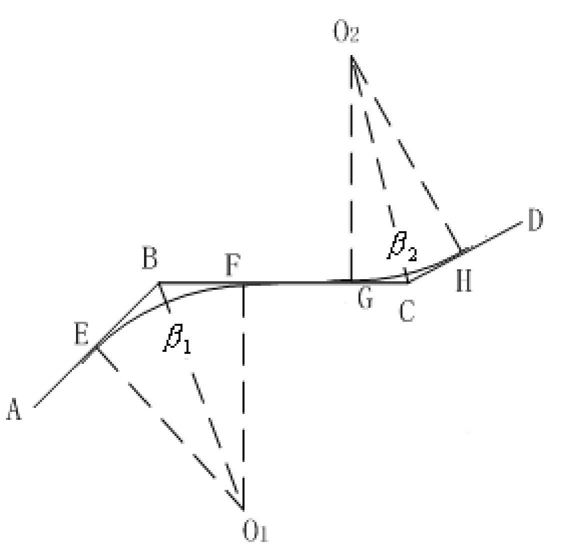

Fig. 5 Path Smoothing

The goal of path smoothing is to replace each angle on the path with an arc that is tangent to each side of the angle. For the tractor-trailer robot is non-holonomic, the radius of the arc should be no less than the minimum turning radius of the robot. If there exist an angle that can't be smoothed, path search should be conducted in the local field to generate continual available routes.

In Fig.5, three adjacent edges AB,BC,CD constitute the local part of the global path acquired in the path search phase. Two angles exist here, one is β_1 between AB and BC and another is β_2 between BC and CD. In the smoothing procedure, two arcs EF and GH are computed to bridge the two angles. The final available path for the non-holonomic robot is in the form of arc-line-arc and each arc should meet the non-holonomic constrain.

Not all the angles can be smoothed for the radius of the arc that bridges an angle may be less that the minimum turning radius of the tractor-trailer robot and can't be tracked by it. See Fig.5, suppose that EO_1 is the vertical bisector of the shorter edge among AB and BC while BO_1 is the bisector of the angle β_1 . Then the radius of the arc EF which is tangent to AB and BC can be computed by the following equation:

$$r_{EF} = \frac{1}{2}\min\{|AB| \ , \ |BC|\} \cdot \tan\frac{\beta_1}{2} \qquad (3)$$

In (3), the symbol $\min\{x, y\}$ denotes that this operation is to pick the smaller from the two numbers.

If $r_{EF} \le R_{\min}$, the angle can't be smoothed and path search should be repeated on the local area, until all edges are smoothed for the non-holonomic robot.

Fig.6 shows the Compound PRM roadmap built and the path planning result based on Compound PRM, where S and G are the start and goal configuration respectively.

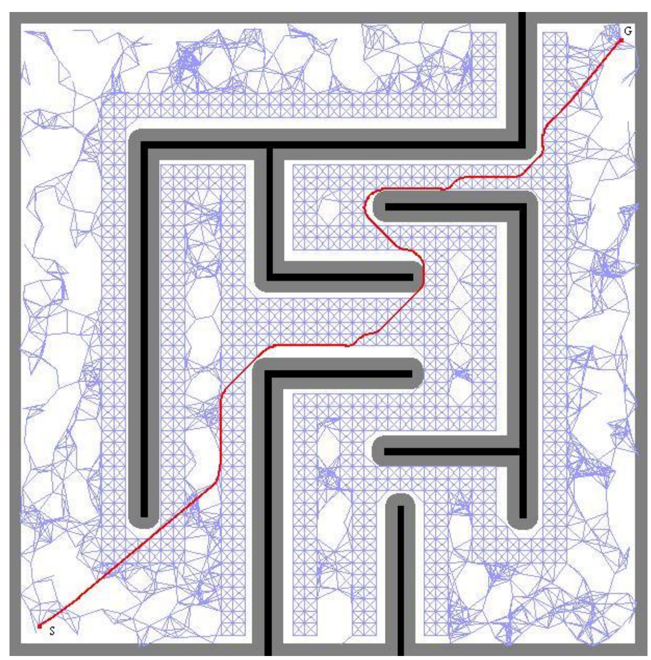

Fig.6 Compound PRM path planning under indoor environment

IV. SIMULATION EXPERIMENT

To validate the performance of the Compound PRM method presented in this paper, a series of simulation experiments are conducted. Suppose that the physical environment where the tractor-trailer robot runs is 10 meters long and 10 meters wide with several obstacles lie in it. Assume that the robot's Equivalent Size is 0.3 meter and its maximum turning angle is 30 degree. The obstacles are expanded as the Equivalent Size of the robot and then the Compound PRM method is used to get a feasible path from the start point to the goal point for the robot.

The simulation results show that by using the Compound PRM method, no available free configuration space is lost. And the Compound PRM method is efficient in both simple environment and complex environment in which the number of obstacles is much more. In complex environments, optimal path can be found using Compound PRM while the time consumed in building the roadmap is relatively long.

Several groups of experiments are conducted to compare the performance of Compound PRM with the conventional Quadtree environment model. Fig.7 and Fig.8 are the results of the two methods. The results show that the Compound PRM method does better than the Quadtree method for the former find a path approximate to a line that directly connect to the start position S and goal position G, while the Quadtree method can only roughly connect the start zone and the goal zone by the point $S^{'}$ and $G^{'}$. And the path found by the Compound PRM method is shorter.

The relative data of the contrast experiments such as the environment set, modeling method and experiment result are listed in TABLE 1. As seen in the table, the statistic result shows that in simple environments with fewer obstacles the efficiency of the Quadtree model is higher than Compound PRM for less time is consumed in modeling though the success rate of path planning is almost the same. But in complex environment, the success rate of Compound PRM exceed Quadtree model much for the Compound PRM modeling is heuristic so that narrow passages can be found. In Table 1, the data in the column Feasible space connectivity shows the degree that the free space can be included into the roadmap while the Compound PRM show master performance in this feature.

Though the modeling phase of Compound PRM is time consuming, the roadmap model needs not to be modified if the environment does not change. This once modeling, multi-query mode makes the Compound PRM method appropriate for usual application environment of tractor-trailer mobile robots such as automatic factory, intelligent warehouse.

V. CONCLUSION

This paper researches the global path planning problem of tractor-trailer mobile robot and presents a Compound PRM environment model which combines local regular roadmap with probabilistic roadmap. Path planning based on Compound PRM can improve the quality of the local path beside obstacles and get an available path that meets the non-holonomic constraint of tractor-trailer mobile robot with minimum computation. Simulation experiment shows that the Compound PRM planning is of high speed and efficiency. For the Compound PRM method has learning capability and can solve the multi-query path planning problem, it is appropriate for path planning in the fixed space where the start and goal configuration change often and the move route need to vary accordingly.

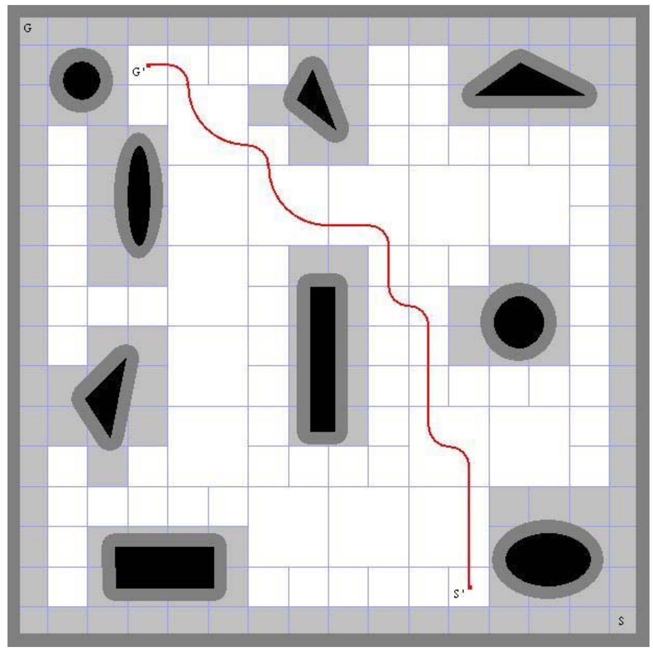

Fig.7 Path planning with Quadtree method

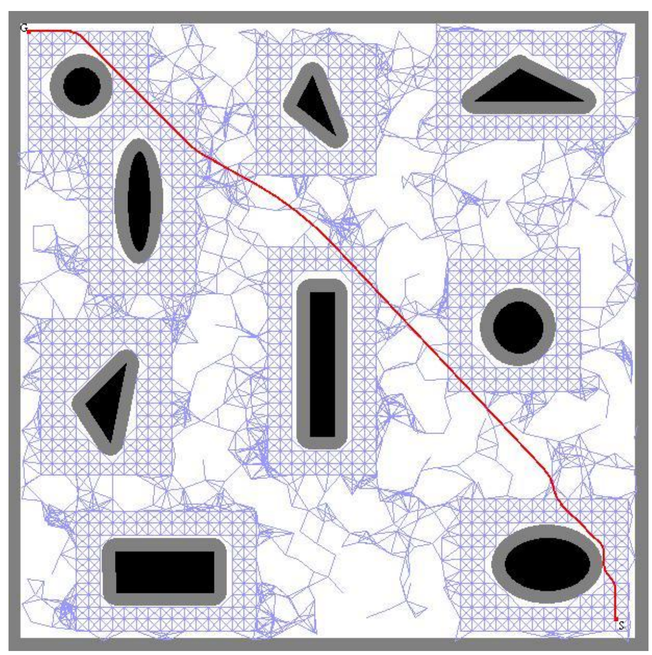

Fig.8 Compound PRM path planning

TABLE I

COMPARE OF SIMULATION RESULT BETWEEN COMPOUND PRM AND QUADTREE METHOD

Planning method	Number of obstacles	Ratio of area occupied	Time by modeling (second)	Time by search (second)	Feasible space connectivity	Ration of successful planning
Quardtree	8	23.64	4.60	1.81	95%	92%
	15	38.65	8.40	1.89	88%	68%
Compound PRM	8	23.64	24.16	1.97	100%	95%
	15	38.65	49.93	2.05	100%	92%

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