Complete Coverage Path Planning of Mobile Robot Based on Dynamic Programming Algorithm

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Keywords: Mobile robot, Complete coverage path planning, Boustrophedon unit decomposition, Dynamic programming algorithm.

Abstract. A complete coverage path planning algorithm, which combines local space coverage with global planning, is proposed. At first, environmental model of mobile robot in a space with obstacles is built by Boustrophedon unit decomposition method, and mobile robot realizes coverage in a reciprocating way in local space. Secondly, it takes local space dividing, sub-space connecting sequence and sub-space walking route into account, then a completely connected distance matrix that represents the connecting relationship of the coverage space are defined. Thirdly, dynamic programming algorithm is used to optimize this matrix and a shortest global coverage sequence is acquired. Simulation example proves the effectiveness of the proposed algorithm.

Introduction

Coverage path planning methods to the mobile robot are different from Point-to-Point (PTP) path planning method [1].It has been applied in cleaning robot, mowing robot and other fields. The coverage path planning is roughly divided into two types: random coverage planning and complete coverage planning. Complete coverage path planning method use some performance evaluation function to control the mobile robot coverage movement to make sure the optimal performances. Types of coverage path planning performance evaluation are coverage efficiencies, percentage of coverage area, coverage overlap rate and energy loss, etc [1,2].

Currently, the coverage algorithm which is commonly used is template model method and cell decomposition method [3]. Because the template algorithm lacks overall planning of the whole environment, so it has low efficiency, besides, the mobile robot can not be handled and easily get into the dead circulation [4]. Template-based complete coverage path planning model requires pre-defined environment model and template memory. Cell decomposition method divides working space of mobile robot into series spaces of non-collision, finite, non-obstacle according to distributions of obstacles and their occupying spaces [5].

In this paper, complete coverage path planning algorithm are studied. At first, complete coverage path planning problem, which combines local space coverage with global planning, are discussed. Secondly, a complete coverage path planning algorithm is put forward based on the combination of cell decomposition method and template model method in a static environment, and the simulation results show the effectiveness of the algorithm.

Coverage Path Planning Based on Dynamic Programming Algorithm

Dynamic Programming Algorithm

The principles of dynamic programming algorithm are partition ideas and solving the problems of redundancy. The ideas of dynamic programming algorithm are decomposing a planning problem into several smaller and similar sub-problems and storage solutions of sub-problems to avoid the repeated calculation of sub-problems. This algorithm is a strategy to solve optimal problems. As long as the problems can be divided into smaller sub-problems and the optimal solutions of the original problems include sub-problem optimal solution, the dynamic programming algorithm can be considered [6].

Complete Coverage Path Planning of Mobile Robot

Geometric method is characterized by simple and high efficient. It is easy for planning and maintenance of the map. Geometric method is relatively intuitive, so it is convenient to construct environmental map, especially for the structured indoor environment. In this paper, environmental map is shown in Fig.1 by using Boustrophedon unit decomposition method; it includes points, lines, and combinations of points and lines which represent the characteristics of the environment. The parameters are used to indicate the specific location of the various features in the environment.

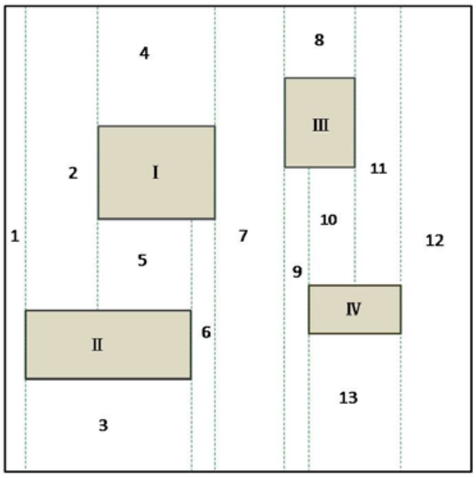

Fig.1 Environmental map based on Boustrophedon unit decomposition

Boustrophedon unit decomposition method uses a virtual line which is parallel to the edges of the rectangular obstacles from left edge to right edge, shown in Fig.1. In Fig.1, coverage areas are generated through the judgment which connects to scanning line. The scanning line starts scanning from the left side of the Fig.1. After environmental map is decomposed with Boustrophedon method, the map is made up by some obstacles area and some coverage area. By Boustrophedon unit decomposition method, the environmental map can be decomposed into some coverage areas and obstacles areas, shown in Fig.1. Because each coverage space has features of two parallel edges and they have public edges of the adjacent area, so through judging each certain public edge to judge whether to an area, and it judges whether reaching to another public edge to judge whether coverage out of an area. In the area through the reciprocating movement, it realizes the coverage. On the basis of the coverage of single area, it needs to determine coverage sequence of the area to reach full environment coverage, which is important to use dynamic programming algorithm to solve the coverage path planning problems.

Fig.2 is the result of Fig. 1 by Boustrophedon unit decomposition method. Normally, it is not easy to carry out coverage algorithm according to the connection relations in Fig.2. Especially, the dynamic programming algorithm requires the visited area joining in the visited forbidden table. In this paper, the space distances are defined by using the connected relationship, distance relationship and obstacles among each area in Fig.1. The existing space connection relationship is further added, which forms a fully connected graph. By definition of Hamilton path, the structure of Fig.2 satisfies conditions of Hamilton channel, so there existing a path which passes each area once and only once access.

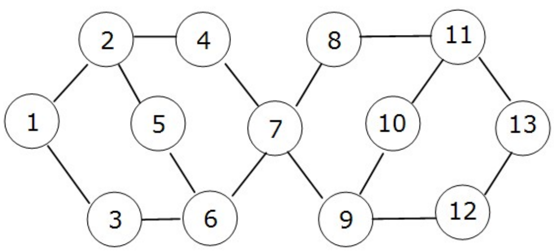

Fig.2 Structure chart based on Boustrophedon unit decomposition

Modeling of Environmental Map for Coverage Path Planning

As shown in Fig.1, the connected distance between space 3 and space 4 areas is not convenient to solve, so a distance is defined to show the actual distance. Although the defined distance and the actual distance has certain gap, but the trend of the distance value is consistent. The definition of distance mainly considers the linear distance between two areas, connected relationship and obstacles situation among the spaces. The distance of adjacent areas is defined *a*, by adjusting *a* to determine a better value through computation. $D' = bDJN'$ is used to describe distances of non-adjacent spaces. Among them, b is a variable coefficient, it can be adjusted through simulation to get a better value. D is a linear distance matrix between two areas in environmental map. According to Boustrophedon unit decomposition method, recent vertex distances between two areas are defined as the linear distance between two areas.

Seen from Fig.2, between space 1and space 2 there exists a connected path. For relations of not one time connected space, it can get n times connecting relation of two spaces through calculating matrix A n times power. For i, j, k three spaces, if space i and j are connected, and space j and k are connected, then space i and area k are connected, also. According to connecting relation in Fig.2, it can be connected through four times at most between any two areas in the environment, so connecting relationship matrix J can be acquired as follows. The closed vertexes between two coverage sub-space are $A(x_i, y_j)$ and $B(x_i, y_j)$. Judging the number of obstacles is the judgment number of the obstacles through AB vector. Obstacles number matrix N among coverage sub-space in environmental map in Fig.1 is shown as follows.

Distance matrix D represents actual distance between coverage sub-space, its element d_{ij} is a shortest vertex distance between sub-space i and j. For the adjacent spaces, the distance value is a. For non-adjacent spaces, the distance is acquired according to space coordinate in environmental map D in Fig.1 is measured as Eq.1. Through multiplication of the same position elements in the obstacles matrix, distance matrix and connected matrix, non-connected area distance multiplied by coefficient b, getting a redefined comprehensive distance matrix D'. Space comprehensive distance matrix D' in Fig.1 are described in Eq.2.

$$J = \begin{bmatrix} 0 & 1 & 1 & 2 & 2 & 2 & 3 & 4 & 4 & 5 & 5 & 5 & 6 \\ 1 & 0 & 2 & 1 & 1 & 2 & 2 & 3 & 3 & 4 & 4 & 4 & 5 \\ 1 & 2 & 0 & 3 & 2 & 1 & 2 & 3 & 3 & 4 & 4 & 4 & 5 \\ 2 & 1 & 3 & 0 & 2 & 2 & 1 & 2 & 2 & 3 & 3 & 3 & 4 \\ 2 & 1 & 2 & 2 & 0 & 1 & 2 & 3 & 3 & 4 & 4 & 4 & 5 \\ 2 & 2 & 1 & 2 & 1 & 0 & 1 & 2 & 2 & 3 & 3 & 3 & 4 \\ 3 & 2 & 2 & 1 & 2 & 1 & 0 & 1 & 1 & 2 & 2 & 2 & 3 \\ 4 & 3 & 3 & 2 & 3 & 2 & 1 & 0 & 2 & 2 & 1 & 2 & 3 \\ 4 & 3 & 3 & 2 & 3 & 2 & 1 & 2 & 0 & 1 & 2 & 1 & 1 \\ 5 & 4 & 4 & 3 & 4 & 3 & 2 & 2 & 1 & 0 & 1 & 2 & 3 \\ 5 & 4 & 4 & 3 & 4 & 3 & 2 & 1 & 2 & 1 & 0 & 1 & 2 \\ 5 & 4 & 4 & 3 & 4 & 3 & 2 & 2 & 1 & 2 & 1 & 0 & 1 \\ 6 & 5 & 5 & 4 & 5 & 4 & 3 & 3 & 1 & 3 & 2 & 1 & 0 \end{bmatrix} \quad N = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & a & a & 15 & 38.1 & 35 & 40 & 55 & 55 & 69.6 & 70 & 80 & 60 \\ a & 0 & 15 & a & a & 28.3 & 25 & 40 & 50 & 45.3 & 55 & 65 & 45.3 \\ a & 15 & 0 & 55.2 & 15 & a & 5 & 68 & 20 & 32 & 40.3 & 45 & 25 \\ 15 & a & 55.2 & 0 & 20 & 20 & a & 15 & 18 & 22.4 & 30 & 40 & 49.2 \\ 38.1 & a & 15 & 20 & 0 & a & 30.4 & 36.1 & 36.1 & 25.5 & 35.4 & 57 & 25.5 \\ 35 & 28.3 & a & 20 & a & 0 & a & 33.5 & 15 & 22.4 & 33.5 & 40 & 20 \\ 40 & 25 & 5 & a & 30.4 & a & 0 & a & a & 35.4 & 15 & 25 & 5 \\ 55 & 40 & 68 & 15 & 36.1 & 33.5 & a & 0 & 20 & 20 & a & 10 & 55.2 \\ 55 & 50 & 20 & 18 & 36.1 & 15 & a & 20 & 0 & a & 26.9 & 20 & a \\ 69.6 & 45.3 & 32 & 22.4 & 25.5 & 22.4 & 35.4 & 20 & a & 0 & a & 36.4 & 10 \\ 70 & 55 & 40.3 & 30 & 35.4 & 33.5 & 15 & a & 26.9 & a & 0 & a & 10 \\ 80 & 65 & 45 & 40 & 57 & 40 & 25 & 10 & 20 & 36.4 & a & 0 & a \\ 60 & 45.3 & 25 & 49.2 & 25.5 & 20 & 5 & 55.2 & a & 10 & 10 & a & 0 \end{bmatrix} \quad (1)$$

$$D'=\begin{bmatrix} 0 & a & a & 30b & 152.4b & 70b & 120b & 220b & 220b & 695b & 700b & 400b & 360b \\ a & 0 & 30b & a & a & 56.6b & 50b & 120b & 150b & 135.9b & 220b & 260b & 453b \\ a & 30b & 0 & 165.6b & 30b & a & 10b & 204b & 60b & 128b & 322.4b & 180b & 125b \\ 30b & a & 165.6b & 0 & 40b & 40b & a & 30b & 36b & 134.4b & 90b & 120b & 196.8b \\ 152.4b & a & 30b & 40b & 0 & a & 60.8b & 216.6b & 216.6b & 102b & 283.2b & 228b & 127.5b \\ 70b & 56.6b & a & 40b & a & 0 & a & 67b & 30b & 67.2b & 100.5b & 120b & 80b \\ 120b & 50b & 10b & a & 60.8b & a & 0 & a & a & 70.8b & 30b & 50b & 15b \\ 220b & 120b & 204b & 30b & 216.6b & 67b & a & 0 & 40b & 40b & a & 20b & 331.2b \\ 220b & 150b & 60b & 36b & 216.6b & 30b & a & 40b & 0 & a & 53.8b & 20b & a \\ 695b & 135.9b & 128b & 134.4b & 102b & 67.2b & 70.8b & 40b & a & 0 & a & 72.8b & 30b \\ 700b & 220b & 322.4b & 90b & 283.2b & 100.5b & 30b & a & 53.8b & a & 0 & a & 20b \\ 400b & 260b & 180b & 120b & 228b & 120b & 50b & 20b & 20b & 72.8b & a & 0 & a \\ 360b & 453b & 125b & 196.8b & 127.5b & 80b & 15b & 331.2b & a & 30b & 20b & a & 0 \end{bmatrix} \quad (2)$$

Simulation Experiments

To the environmental map in Fig.1, where I, II, III, IV are four obstacles. Simulation system is developed by VB software. During computation parameter a=0.1 and b=1 are selected. The optimization sequence of coverage space in Fig.1 is: 1-2-4-8-11-10-9-12-13-7-6-5-3, simulation results are shown in Fig.3.

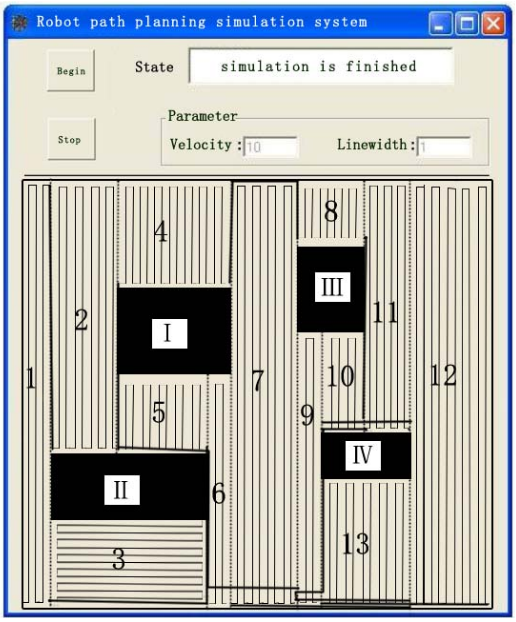

Fig.3 Simulation results

Conclusion

According to space relations and space connected graph in the coverage environmental map, the connected graph is supplement for fully connected graph. According to the connecting information, this paper defines a distance matrix of the environmental map and its connection weights among structures. Space coverage sequences were optimized by dynamic programming algorithm according to this distance matrix. Simulation results show that this method guarantees mobile robot coverage all reachable working space, and path repetition rate is small.

Acknowledgements

This work is supported by the Tianjin Science and Technology Key Research Program (10ZCKFSF01500), the Research and Development Projects of Tianjin University of Technology and Education (YY09006, KJY1106).

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Published by Atlantis Press, Paris, France.