A Distributed and Optimal Algorithm to Coordinate the Motion of Multiple Mobile Robots

Jianying Zheng  
Shenyang Institute of Automation  
Chinese Academy of Science(CAS)  
Shenyang, Liaoning Province, China  
zhengjy@sia.ac.cn

Haibin Yu, Wei Liang, and Peng Zeng  
Shenyang Institute of Automation  
Chinese Academy of Science(CAS)  
Shenyang, Liaoning Province, China  
{yhb, weiliang&zp}@sia.ac.cn

Abstract – This paper addresses the problem of planning paths for multiple mobile robots moving in the same environments. We try to decrease the computational complexity of path planning, which is one of the fundamental limiting characteristics in the existing work of path planning. Unlike many other approaches to this problem, we assume the robots are restricted by the limited-communication range such that information about other robots can be known only when they move close to each other. In our method, the computationally expensive problem is decomposed into two modules—path planning and velocity planning. Such decomposition makes approaches of path planning for multiple mobile robots applicable. Trajectory for each robot is achieved by using the approach named Vector Field Histogram (VFH) before the robots begin to move. Then the conflicts among robots are solved by adjusting the velocities of robots. Velocity planning occurs only inside the robots that are in the same network. The method of planning velocities for the robots is called the dynamic priority assignment, which can minimize the total waiting time of robots in the same network. Finally, both simulated and real-robot experiments have validated our approach.

Keywords—multiple mobile robots, motion planning, distributed control, dynamic robot network, limited communication range.

I. INTRODUCTION

This paper examines the problem of planning paths for multiple mobile robots working in the same environments. In multi-robot robot systems, path planning is one of the fundamental issues necessary to be solved. As we known, motion planning algorithms for a single mobile robot have been intensively discussed for several years (see the survey book [19]). In an environment containing a set of stationary obstacles, path planning methods such as graph search method based on geometric configuration of the environment can guarantee the attainment of optimal paths in polynomial time, if one exists. However, motion planning in dynamic environments with moving obstacles or other robots is inherently harder. Such a problem is NP-hard and cannot be solved in polynomial time. For example, computing a collision-free path for an object with n degrees of freedom among static obstacles takes time exponential in n; computing a collision-free trajectory for an object with few degrees of freedom among p moving obstacles takes time exponential in p. This fact makes motion planning for multiple mobile robots a very difficult problem, which becomes the focus of attention in the field of multi-robot systems.

According to the previous literature, simple reactive motion planning approaches cannot guarantee deadlock-free and convergence, even in simple situations. However, many applications in wide domains require practical and efficient motion planning strategies. Thus the approaches based on planning become the alterative choice to multi-robot motion planning. A number of algorithms have been proposed to achieve collision-free and deadlock-free paths in the past few years. However, most of these algorithms can work in limited domains, and are too complex to be applicable. This paper makes contributions on proposing distributed and network-based algorithm to coordinate the motion of multiple mobile robots.

In this paper, we have decomposed the motion planning into two modules-path planning and velocity planning. Such decomposition can greatly decrease the computational complexity of motion planning. The trajectories that robots move along are achieved by using the method named Vector Field Histogram (VFH) before the robots begin to move. These trajectories are fixed after determination. However, the velocities can change during their movement. Due to limited communication range, the robots can find other robots when they move to the same network where the robots can communicate with each other. If the conflicts are detected, the robots will try to solve them by using the method of dynamic priority assignment. With this method solving the conflicts, the waiting time of robots in the same network can be minimized; that is to say, the total time of robots from their initial points to end points is minimized. Therefore, with our algorithm, the robots can successfully reach their goals and can optimize the total waiting time during movement. Finally, our algorithm is demonstrated by simulated and real-robot experiments. The results show that our method can successfully coordinate the motion of multiple mobile robots moving in the same environments. In addition, our method is available for those applications where the robots have limited communication range.

The remainder of this paper is organized as follows. Section II describes the related work in the field of multi-robot motion planning. Section III formulates the problem and offers some assumptions. Section IV provides the multi-robot motion
planning algorithm in this paper. Section V shows simulation and experimental results to demonstrate the performance of our algorithm. Section VI draws the conclusions and discusses the future work.

II. RELATED WORK

The existing multi-robot motion planning algorithms are often categorized as centralized or decentralized according to the information handling structure among robots. The most straightforward method is centralized motion control where the central planner determines non-conflict paths for all the robots operating in the same workspace. Centralized planners can be advantageous because they allow the possibility of completeness and global optimization. However, the centralized methods are not suitable to the situations involving a large number of robots working in the same environments because they take time exponential in the number of the robots or moving obstacles. Centralized motion planning work is shown in [6], [7], [8], [9], [10], among which [7] and [9] assign priorities to robots in advance. Another form of centralized approach is the approach using master-slave control proposed in [10]. Once a conflict occurs, one of the conflicting robots will be selected to be the master, who will solve the conflicts and transmit motion instructions to other robots involved in the current deadlock. In decentralized planning, each robot plans individually for itself by means of collecting information from other robots and environmental information around the robot. Decentralized planning work includes [12], [13], and [14]. In [12], dynamic priority assignment negotiation is used to coordinate the motion of multiple mobile robots; in [13], a robot is randomly selected to stop and insert random delay to solve the potential collision; in [14], a decentralized approach based on traffic rules has been proposed, and such rules are primarily applicable to environments which are modelled as a route network.

Motion planning in dynamic environments was originally addressed by adding the time dimension to the robot’s configuration space. The technique proposed in [6] discretizes the configuration-time space into a sequence of slices of the configuration space at successive time intervals, and represents the motions of moving obstacles using the set of slices embodying space-time. The disadvantage of this approach is that the complexity computation arises with respect to the number of robots and the size of workspace. Consequently, another approach to multi-robot motion planning is proposed in [15]. The approach decomposes motion planning into path planning and velocity planning. The decomposition greatly decreases the complexity computation caused by the additional time dimension, and can be easily applicable to those situations where robots move along fixed paths. A number of studies have been made based on path-velocity decomposition. In [16], a similar idea is proposed to plan for two robots operating in a common environment. This paper will follow the principle of path-velocity decomposition design, and obtain a distributed and optimal algorithm to coordinate the motion of multiple mobile robots working in the same workspace.

Many approaches have been proposed for path planning, for example, Artificial Potential Filed (APF), Vector Field Histogram (VFH), and Probabilistic Roadmap Approaches (PRM). These approaches are three kinds of typical approaches. The APF algorithm was first proposed by Khatib in [21], but this method is limited by local maxima. However, the VFH algorithm proposed in [20] is totally different from the APF algorithm. The VFH algorithm considers all possible moving directions, among which the one with the lowest cost is selected as the one to be executed. In addition, comparing to another path planning approach named PRM, the VFH algorithm can achieve real-time solutions, especially in partially known environments. The VHF approach is also used in this paper to plan paths for each robot.

III. PROBLEM DEFINITION AND ASSUMPTIONS

This paper focuses on motion planning for multiple mobile robots. Therefore, other issues, which have been described in [17], are beyond of the scope of this paper. The premises and assumptions in this paper are stated as follows.

1. Each robot has an assigned task, and each robot knows its start and goal positions.
2. The environment where robots are operating is totally known to each robot, that is to say, each robot has a pre-defined map obtaining from sensors on each robot.
3. Robots will not break down while they are executing their tasks.
4. Each robot is equipped with a communication device with limited communication range, that is to say, only two robots who locate within each other can establish a communication link. In addition, the communication device can be capable of transmissions, that is to say, any two robots can exchange information if they can communicate with each other through one or several communication links.
5. The planned trajectories will be tracked within a small margin of error by the robot’s motion control.
6. Robots move at a fixed speed, which cannot exceed the maximum speed they can move.
7. Robots can switch between a fixed speed and halting immediately.

Based on these assumptions above, we can define the multi-robot motion planning problem as follows.

We have to find a sequence of points for each robot \( R_i \), \( (i = 1, 2, \ldots, N) \) connecting its beginning point \( S_i \) with its goal point \( G_i \), without collisions with static obstacles and other robots, while minimizing the following global performance index:

\[
T_j = \sum_{i=1}^{n} W_i \]

(1)
Where \( j \) represents the \( j^{th} \) network or the \( j^{th} \) planning, \( W_i \) represents the waiting time of the \( i^{th} \) robot, \( n \) represents the number of robots in the same network \((n \leq N)\), \( T_j \) represents the total waiting time of the robots in the \( j^{th} \) network.

By minimizing the performance index \( T_j \), we can minimize the total waiting time of all robots because \( T = \sum_{j=1}^{M} T_j \) where \( M \) represents the whole number of the network.

IV. MULTI-ROBOT MOTION PLANNING ALGORITHM

The main flow chart of the algorithm is shown in Fig.1. First, each robot is able to plan its own path using the approach of Vector Field Histogram (VFH). The paths planned for each robot will be fixed, that is to say, the following steps will not allow change to the \((x, y)\) sequences of the paths. Once the paths are planned, each robot will search those robots who can communicate with it through one or several communication links. These robots will form a network and exchange path information with each other. After acquiring path information of other robots in the same network, conflicts among robots will be coordinated by negotiation based on dynamic priority assignment. The negotiation results with the lowest cost value will be selected as the one to be executed. However, if new robots are found by any robot in the network, the process will be executed again except path planning.

The following subsections will discuss more details about the algorithm used in this paper.

A. Path Planning

Assume robot \( R_j \) moves on a workspace \( \Omega \subset \mathbb{R}^2 \), and the obstacle space is \( \Omega_{\text{obstacle}} \subset \mathbb{R}^2 \). The obstacle space defines regions where robots cannot travel due to mission constraints (for example, minefields) or undetectable navigation challenges (for example, quicksand). In order to make robots safe absolutely, a safety margin by a positive constant \( \varepsilon \) is defined, and \( \Omega_{\text{prohibited}}^\varepsilon \) is the space that is within \( \varepsilon \) distance of \( \Omega_{\text{obstacle}} \). The valid search space can be denoted as \( \Omega_{\text{free}} = \Omega \setminus \Omega_{\text{prohibited}}^\varepsilon \). Therefore, the path planning task is to find a sequence of geometric points from the start position to the goal position in \( \Omega_{\text{free}} \) according to the environment map obtained by sensors on each robot.

Path planning algorithm is totally distributed in this paper, that is to say, each robot plans its own path independently according to the environment information obtained by its own on-board sensors. The output of this module is a path \( P_i \) for robot \( R_i \), which consists of a sequence of geometric points the robot is to pass through, in the resolution of the grid of the environment map. Path \( P_i \) is then be shared all other robots who can communicate with robot \( R_i \) through one or several communication links.

B. Velocity Planning

Velocity planning, which can be divided into network formation and conflicts coordination, aims to solve conflicts among robots by tuning robots’ velocities. The work done by the module of network formation is to search all robots who can communicate with each other through one or several communication links; these robots will form a network dynamically and share path information with each other once a new network is formed. After obtaining path information of other robots, it is needed to resolve conflicts among robots, which is handled by the module of conflicts coordination. Negotiation method based on dynamic priority assignment is used. More details will be discussed below.

1) Network Formation

Module of network formation aims to the group of conflicts coordination. When any two robots are within communication range of each other, they establish a communication link. We define \( G \) as the graph whose nodes are the robots and edges are the communication links. A network of robots is any group of \( k \geq 1 \) robots forming a maximal component of \( G \). Therefore, any two robots within the same network can communicate with each other through one or several communication links and share path information with each other, but two robots from different networks cannot.
This process of forming networks is illustrated in Fig.2 on a simple example involving three robots, with no obstacles. A triggering event automatically occurs at the start of the process, as the first networks get formed.

a) All three robots (grey circles) are at their initial locations. The two left robots are in communication range and form a network. While the right robot forms another network involving itself. (Note that the corresponding goals are denoted as cross-hairs.)

b) As the robots move along their trajectories, the middle robot and the right enter communication range with each other, and all three robots now form a large network.

Fig. 2 a) and b) show the process of network formation involving three robots.

2) Conflicts Coordination

After obtaining path information from other robots within the same network, robots will check collisions between robots and coordinate conflicts by the way of negotiation based on dynamic priority assignment that has been intensively addressed in [12]. In this approach, each priority order will be checked; the corresponding performance index will be calculated and shared in the network. Then an evaluation will be done to compare each performance index in order to select the one with the lowest performance index to be executed. By assigning dynamic priorities to robots, conflicts among robots can be efficiently solved relative to assigning static priorities to robots.

V. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulations

For verification of the described algorithm, simulations with user-defined number of robots have been developed. Here, we have considered the situation where three robots were moving from each start positions to their corresponding goal positions. The workspace was given dimensions 10m×10m, and was represented as grids whose dimensions were given 0.01m×0.01m. Static obstacles were set according to requirements of real-world environments earlier than planning paths for robots.

Simulation results are shown in Figure 3 and Figure 4. Trajectories robots will follow are shown in Figure 4, where robot start positions and goal positions are respectively denoted as S1, S2, S3 and G1, G2, G3. The paths planned for each robot have been described by dash lines with different colour. The results demonstrate that the VFH approach can plan paths for each robot efficiently. The corresponding velocity profile is shown in Figure 4. The first time to coordinate conflicts happens once robot 2 and robot 3 have planned paths for themselves. Robot 2 and robot 3 can form a network, and share path information with each other. Velocity profiles show that the solution to solve conflicts is to insert five unit time delays for robot 2 at the beginning of its movements. Along with movements of robots, robot 2 can communicate with robot 3 and robot 1. Consequently, robot 1, robot 2 and robot 3 can form a new network, and share path information with each other. Velocity profiles show that the solution to solve conflicts among three robots is to inserting six unit time delays for robot 1 at the middle of its movements. Such scheme described above is the best solution to coordinate conflicts among robots, because the scheme holds the lowest performance index. (Note that the performance index is defined as the minimum sum of the most expensive time to reach robot goals and total idling time of all robots).

Fig. 3 Simulation results with matlab. Here, S1, S2, S3 denote the start positions of each robot respectively, and G1, G2, G3 denote the goal positions.

Fig. 4 Velocity profiles of 2D simulations.

B. Real-Robot Experiments

To illustrate the applicability of the algorithm to a physical system, we have carried out experiments involving five robots, among which three robots are moving and the other two robots are considered as static obstacles. Such design is in favour of research work with dynamic obstacles. An overhead vision sensor is used to track states of all objects in the workspace. The vision system processor calculates these states and publishes them to all applications that subscribe. This makes all global state information available to all robots. In order to simulate limited sensing range that would occur when sensors are mounted on robots, the objects states are
filtered such that robots only receive state information that regarding objects within some preset range of the robot. The way of dealing limited sensor range is also suitable to robots with limited communication range, and is used in real-robot experiments.

Then, conflicts are coordinated again in the new network. Experiments on real-robot have demonstrated that the algorithm can meet strict real-time performance requirements and can efficiently resolve conflicts among robots through negotiation. In addition, we have overcome the robot constraint of limited communication range well with dynamic robot network.

VI. CONCLUSIONS AND FUTURE WORK

This paper addresses the problem of motion planning for multiple mobile robots working in the same environments. We provide a distributed and optimal algorithm to coordinate the motion of multiple mobile robots. Our algorithm can minimized the waiting time of robots so that the robots can arrive at their goals as soon as possible. Both simulated and real-robot experiments have demonstrated the effectiveness of our algorithm in planning paths for multiple mobile robots working in the same environments.

The future work will be improved further in three directions. The first is applying the algorithm to more sophisticated environments, for example, 3D environment or environment with moving obstacles. The second is to investigate the performance of our algorithm when the communication range is varying. The last one is to scale up our algorithm to the situations involving more than a dozen robots.

ACKNOWLEDGMENT

This work is supported by the Natural Science Foundation of China under contact 60374072, 60434030, 60704046, 60725312, Doctor Foundation of Liaoning Province of China under contact 20041004, and Excellent Young Leader Foundation of Liaoning Province of China under contact 3040004. Thank Dr. Zheng Wei for his help with building the real-robot experiment platform.

REFERENCES


