A Negotiation-Based Collision Avoidance Scheme for Autonomous Mobile Robots

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Abstract. Autonomous mobile robots become increasingly more popular in many fields to execute tasks instead of human beings. When multiple autonomous mobile robots coexist in an area and move autonomously, how to avoid collision among them is a critical issue. In this paper, a distributed negotiation-based collision avoidance scheme is proposed. With this scheme, mobile robots negotiate with each other when they are about to collide. Based on the negotiation, the robots make the most appropriate decision to avoid collision, and move forward to their own destinations with the least cost. The effectiveness and the efficiency of the proposed scheme are proved by extensive simulations.

Keywords: Autonomous mobile robot · Collision avoidance
Negotiation

1 Introduction

Autonomous mobile robots, which are currently undergoing a period of rapid development, have been employed in many fields to undertake tasks instead of humans. For instance, in a warehouse of Amazon, hundreds of autonomous mobile robots are busy in carrying goods. Once online orders are generated, these robots fetch the goods listed in the order from a mass of shelves. Moreover, a increasing number of factories, hypermarkets, logistics companies begin to use mobile robots to fulfil tasks such as sorting, transporting, placing objects, and so on. With the help of autonomous mobile robots, workloads for human employees have been alleviated greatly, and working efficiency has been improved dramatically.

When multiple robots coexist in an area and move autonomously, how to avoid collision among them is a critical problem. If the problem is solved in a centralized way, a central controller is needed in the system. The controller collects current positions and moving states of all mobile robots, and computes moving paths for every robot. However, single-point failure is an inherent problem of the centralized scheme. Moreover, the centralized scheme is not flexible enough, because its scalability is limited by the number of mobile robots. When the number of robots is large, the computation becomes time-consuming, which

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is not suitable for real-time control for robots. Hence, a distributed mechanism is preferred in practical scenarios.

In this paper, a negotiation-based collision avoidance algorithm for autonomous mobile robots is proposed. The algorithm operates in a distributed manner. Each mobile robot senses its surrounding environment, and negotiates with related robots when a collision is about to happen. They exchange their urgency degrees or the optional moving directions. Based on the negotiation, a robot decides whether to give way to the other robot. The concessive robot also selects a new moving direction. In order to measure the moving efficiency of robots, a metric called actual time to theoretical time ratio (ATR) is utilized. Extensive simulations are conducted to verify the effectiveness and the efficiency of our proposed algorithm.

Many previous work focus on path planning [1–3] or group communication protocols [4,5] for mobile robots. To the best of our knowledge, we are the first to put forward a distributed negotiation-based collision avoidance algorithm for autonomous mobile robots. Our contributions are summarized as follows:

(1) A new metric, which is actual time to theoretical time ratio (ATR), is defined to measure the moving efficiency of mobile robots.
(2) A concessive robot decision algorithm is put forth. The algorithm is based on the urgency degrees or the number of optional moving directions.
(3) A moving direction selection strategy for concessive robot is proposed. The new moving direction is selected based on the shortest distance.
(4) A simulator is developed to evaluate the performance of the collision avoidance scheme. Both effectiveness and efficiency of the scheme are verified.

The remainder of the paper is organized as follows. Related work is summarized in Sect. 2. The system model and the problem is described in Sect. 3. The negotiation-based collision avoidance algorithm for autonomous mobile robots is elaborated in Sect. 4. The results of extensive simulations are shown and analyzed in Sect. 5. Finally, the paper is concluded in Sect. 6.

2 Related Work

Path planning and navigation has been a research hotspot in the field of mobile robots for many years. Surveys are given in [1,6]. A number of previous works focus on planning a path for a mobile robot to avoid static obstacles [2,7] or moving obstacles [3]. In [8], a method of collision avoidance based on rules and communication proposes, which combines the local environmental model with the dynamic scene. But it just be appropriate for two robots, and can not deal with the situation that two robots have the same priority. With the development of artificial intelligence, some researchers begin to solve the problem based on computer vision [9]. A real implementation is reported in [10].

Since method in [2] is centralized, distributed solutions are proposed in [3,7,11]. In [3,11], collisions of mobile robots are avoided by adjusting the speeds of the robots. These methods are not fit for the scenario that the speed cannot be adjusted arbitrarily. In [7], a virtual repulsion-like force is introduced. The force between two mobile robots is determined by the distance between them. Hence, a mobile robot decides its moving direction according to the distance between it and other robots. However, this solution cannot minimize the moving time cost of the robots.

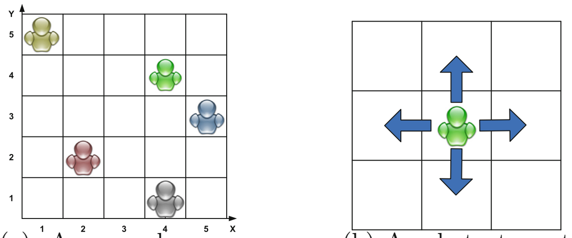
In [4], an efficient group communication protocol for mobile robots is designed. Furthermore, the authors of [4] present a mobility-aware ad hoc routing protocols for mobile robot teams in [5].

In this paper, we design a distributed negotiation-based collision avoidance mechanism. When two mobile robots are about to collide, one of them gives way to the other one based on the negotiation, and the moving time cost is minimized. This scheme has not been put forward in previous work. In this paper, mobile robots negotiate with each other using short distance communication technologies, such as WiFi, Bluetooth, ZigBee, etc. Once a wireless link is set up between a pair of mobile robots, they can transmit information mutually. Routing protocols are not necessary in our scenario.

3 System Model and Problem Description

3.1 System Model

The scenario considered in this paper is that a group of autonomous mobile robots are distributed randomly in a two-dimension (2D) rectangular area, as demonstrated in Fig. 1(a). The number of the robots is m, and the robot group can be represented by an m-dimension vector $<R_1, R_2, \cdots, R_m>$. The area is divided into $X \times Y$ grids of the same size. Each grid can only accommodate one robot. Thus, the position of a robot can be indicated by the coordinates of the grid in which the robot locates. Specifically, the location of the i-th robot is $L(R_i) = (x_i, y_i)$, where $1 \leq i \leq m$, $1 \leq x_i \leq X$, $1 \leq y_i \leq Y$, and $i, x_i, y_i \in \mathbb{N}$. Suppose each robot knows its position at any time via a certain positioning technology.



(a) A sample scenario of multiple autonomous mobile robots in an area

(b) A robot at most has four possible moving directions

Fig. 1. System model

The goal of each robot is to move from its initial location to a predetermined destination. The initial location of robot R_i is denoted as $L(R_i)_{start} = (x_i^{(s)}, y_i^{(s)})$, and its destination is $L(R_i)_{des} = (x_i^{(d)}, y_i^{(d)})$. It is assumed that each robot can only move towards four directions, i.e., forward, back, left, and right, as shown in Fig. 1(b). Therefore, the distance between two locations for robots is measured as the Manhattan distance. The distance between the starting point of R_i and its destination is $D(L(R_i)_{start}, L(R_i)_{des})$, which is computed as:

$$D(L(R_i)_{start}, L(R_i)_{des}) = |x_i^{(d)} - x_i^{(s)}| + |y_i^{(d)} - y_i^{(s)}| \tag{1}$$

The moving speed of R_i is represented by $S(R_i)$. In this paper, all mobile robots are supposed to move at the same speed. The time that a robot can move from one grid into a neighboring grid is viewed as a time slot. In other words, the distance that a robot can move in a time slot is 1. Thus, the theoretical moving time of R_i from beginning to arrival is denoted as $T(R_i)$, which is computed by:

$$T(R_i) = \frac{D(L(R_i)_{start}, L(R_i)_{des})}{S(R_i)} \tag{2}$$

As demonstrated in Fig. 2, there are two cases that lead to potential collisions between two mobile robots. In Case 1, two robots will move to the same grid in the next time slot. In Case 2, the current position of a robot is the expected position of the other robot, and vice versa. In order to avoid collision, each robot needs to have the ability of sensing and communication. The sensing ability can be achieved by equipping robots with sonar ranging sensors, and the communication ability can be attained through short-range wireless communication technologies, such as WiFi, ZigBee, Bluetooth, etc. Once a robot perceives a potential collision, it avoids the collision through negotiating with the other robot. According to Case 1, the minimal sensing range and the minimal communication range of a robot are both set to 2.

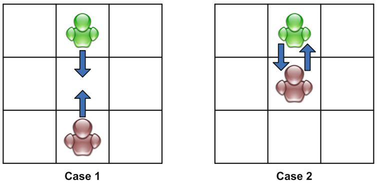


Fig. 2. Two cases of potential collision between two mobile robots

Since a robot may make a detour or stay to avoid collision during the move, its actual moving time, expressed by $A(R_i)$, is no less than the theoretical moving time between the starting point and the destination:

$$A(R_i) \geq T(R_i) \tag{3}$$

3.2 Problem Description

Given starting positions and predetermined destinations of all mobile robots, the total moving time of all robots, recorded as $\mathbb{T}$, is:

$$\mathbb{T} = \sum_{i=1}^{m} T(R_i) \tag{4}$$

The total time of all robots actually move, denoted as $\mathbb{A}$, is calculated by:

$$\mathbb{A} = \sum_{i=1}^{m} A(R_i) \tag{5}$$

According to inequality (3), the following relationship holds:

$$\mathbb{A} \geq \mathbb{T} \tag{6}$$

In order to improve moving efficiency of all robots, $\mathbb{A}$ should be minimized. Since the starting positions and the destinations of all robots are randomly chosen, the absolute value of $\mathbb{A}$ cannot reflect real moving efficiency. For the sake of fair comparison, actual time to theoretical time ratio (ATR) is put forward as a new metric:

$$ATR = \frac{\mathbb{A}}{\mathbb{T}} \tag{7}$$

Consequently, the objective of the problem is formalized to minimize ATR as follows:

$$minimize \quad \frac{\mathbb{A}}{\mathbb{T}} \tag{8}$$

s.t. Eqs. (1), (2), (4) and (5).

4 Negotiation-Based Collision Avoidance Scheme

When two robots come into a situation that they will collide in the next time slot as shown in Fig. 2, one of them should change its planned moving direction to avoid the potential collision. Since no centralized controller exists in the system and decisions are made in a distributed manner, three questions are raised. The first question is that which robot should make a concession and alter its planned moving direction. The second question is that, when a robot has to change its moving direction, how to select a new direction for the robot. The last one question, when the number of robots is more than two, how to deal with the collision among them. In this section, all these issues are settled.

4.1 Decision on Concessive Robot

Due to lack of centralized controller, two robots with potential collision should coordinate their moving directions by themselves. Hence, a negotiation-based scheme is designed. With this scheme, two robots establish a wireless link between them, and exchange necessary information. Based on the exchanged information, both robots make a consistent decision that which one keeps its planned route unchanged, while the other one changes its moving direction. In terms of whether robots have different urgency degrees, how to reach an agreement between two robots is discussed in the following two cases.

Case 1: Robots have different urgency degrees. In a practical scenario, robots that fulfil various tasks may have different urgency degrees. Under this circumstances, two robots exchange their urgency degrees, and the robot with lower urgency degree should make a concession. In this way, the robot with higher urgency degree keeps its route unchanged without making a detour, thus it can arrive its destination as soon as possible. Since the robot with lower urgency degree has to yield, it inevitably leads to longer moving time than its expectation. In order to minimize the metric of ATR, how to select the next step is discussed in Sect. 4.2. If two robots are with the same urgency degree, which one to make a concession is determined as explained in Case 2.

Case 2: Robots have the identical urgency degree. If all robots have the identical urgency degree, a new criterion is needed. The number of optional moving directions is utilized as the new criterion. A robot at most has four optional moving directions. If one or more possible moving directions are blocked by other robots or obstacles, or the robot just locates at the boundary of the region, the number of optional moving direction decreases. As depicted in Fig. 3, the robot R_1 has two optional moving directions (marked by stars), while R_2 has three (marked by circles). After exchanging the number of optional moving directions, the robot with more options changes its planned route, because it has more choices.

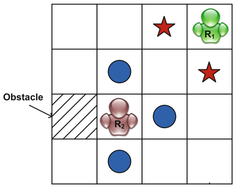


Fig. 3. Examples of the number of optional moving directions

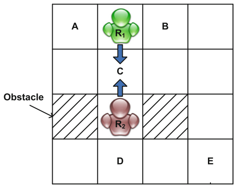


Fig. 4. An examples of decision on concessive robot when robots have the identical urgency degree

An example is demonstrated in Fig. 4. Robots R_1 and R_2 both plans to move into the same grid (marked by C) in the next time slot, and there is a potential collision. Thus, they need to negotiate, and their optional moving direction numbers are exchanged. Robot R_1 has three options (i.e., A, B, and C), while R_2 has two (C and D). As a result, R_1 has to make a concession, and changes its planned moving direction. To give way to R_2, R_1 can move into A or B in the next time slot.

If two robots have the same number of next-step options, a winner between them is selected randomly based on a certain distributed algorithm. For instance, each robot generates a random number to compare. It can be appointed that the robot with larger (or smaller) number makes a concession.

4.2 Decision on Moving Direction

Once a robot is determined to alter its moving direction based on the negotiation, it should decide where to move in the next time slot. In order to reduce the cost incurred by the detour, the robot selects the position that has the shortest distance to its destination among all the options. Take Fig. 4 for example again. Suppose E is the destination of R_1. R_1 selects B as its next position, because the distance between B and E is shorter than the distance between A and E.

If all its optional moving directions are blocked, the robot stays at the current position in the next time slot, and its actual moving time still increases by 1.

4.3 More Discussions

In the case that more than two robots are about to collide, the solution is similar. Each robot broadcasts its urgency or the number of optional moving directions to other relevant robots. If they have different urgency degrees, the robot with higher urgency has higher priority to select moving direction. If relevant robots have the same urgency degree, the robot with less optional moving directions has higher priority to move.

In some particular cases, the priority of two mobile robots are alternated after a negotiation, and they may move between one location and next location. In order to break such deadlock, each robot should record the locations that it has passed. If it finds itself enters a loop, another strategy should be used for breaking out. Due to page limitation, the detailed solution will be described in the extended version of this paper.

5 Performance Evaluation

5.1 Simulation Setup

In order to evaluate effectiveness and performance of the proposed scheme, a simulator is developed using Java programming language. In the simulator, multiple mobile robots are distributed in a 2D region. The starting positions and destinations of all robots are generated randomly following a uniform distribution. Once a simulation starts, each robot moves a distance of 1 in a time slot. The robots move along one dimension (e.g., along X axis) first, then move along the other dimension.

Our proposed concessive robot selection is based on negotiation. For comparison, a random selection strategy is also used in simulations. The recommended new moving direction of the concessive robot is selected based on shortest route. A random selection strategy is also employed for comparison. The four schemes implemented in the simulations are listed in Table 1. Our proposed scheme is abbreviated as NS, the other three are NR, RS, and RR, respectively.

Table 1. Four schemes are implemented in the simulations

Scheme abbreviation	Concessive robot selection	Moving direction selection
NS	Negotiation	Shortest
NR	Negotiation	Random
RS	Random	Shortest
RR	Random	Random

Simulations are conducted to evaluate performance under following two cases, respectively.

Case 1: Robots have different urgency degrees. In this case, three different urgency degrees are set, i.e., low, medium, and high. Each robot is randomly assigned a urgency degree from the three levels. The size of the area is 100 × 100, and the number of robots is set to 100.

Case 2: Robots have the identical urgency degree. In this case, all robots have equal urgency degree. The size of the area is 100 × 100. The number of robots is set to 200. Fixed obstacles are distributed in the area following a uniform distribution. The proportion of fixed obstacles varies from 0.01 to 0.03. In another settings, the proportion of fixed obstacles is 0.01, and the number of mobile robots varies from 100 to 300.

A simulation under one setting repeats ten times, and the average results are shown in the following.

5.2 Simulation Results

Case 1: Robots have different urgency degrees. When the number of robots is 100, ATR of robots with different urgency levels are displayed in Fig. 5. With the NS scheme, robots with high urgency degree have the lowest ATR, which means high-urgency robots arrive at their destinations consuming less time. Due to concession made by low-urgency robots, they need to spend more time to move. The results are in accordance with expectation. With other three schemes, it cannot ensure that the robots with high urgency consume the least time.

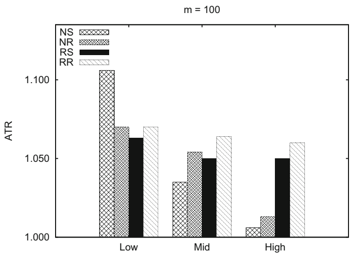


Fig. 5. Performance with different urgency degrees when $m = 100$

Case 2: Robots have the identical urgency degree. As indicated in Fig. 6, performances of the four schemes with varied fixed obstacle are compared. The NS scheme has the lowest ATR, which outperforms other three schemes. The ATR of RS is a little higher than NS, which implies that it is significant to choose a new moving direction for the concessive robot based on the shortest distance. The ATR values of both NS and RS increase slowly with the increase of fixed obstacle proportion, while the ATRs of NR and RR have higher growth rate. As expected, the scheme of RR has the highest ATR.

When the proportion of fixed obstacles is 0.01, and the number of mobile robots varies from 100 to 300, the performances of the four schemes are shown in Fig. 7. With the increase of robot number, ATRs of all schemes grow. However, the NS scheme always has the lowest ATR, and RR has the highest ATR. It can be concluded that the negotiation-based concessive robot selection and the shortest distance-based moving direction selection strategies are effective and efficient.

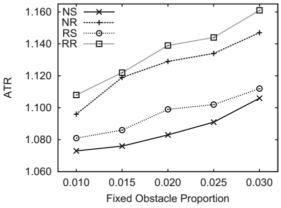


Fig. 6. Performance with varied fixed obstacle proportions

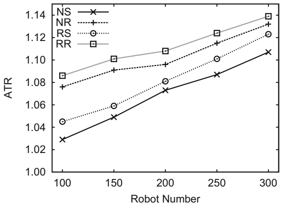


Fig. 7. Performance with varied mobile robot densities

6 Conclusion

In order to avoid collision when multiple autonomous mobile robots coexist in an area, a negotiation-based scheme was put forward in this paper. With the scheme, a robot that should make a concession was selected, and the direction it should move forward was also decided. Extensive simulations proved the effectiveness of the scheme. Implementation of this scheme on a real test is subject to future research.

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