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COLLISION AVOIDANCE AMONG MULTIPLE MOBILE ROBOTS BASED ON RULES AND COMMUNICATION

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ABSTRACT

An autonomous and decentralized robot system, ACTRESS, is being developed as an intelligent robot system which is composed of multiple robotic agents. In this paper, basic concept and strategy for path planning in a dynamically changing environment where multiple autonomous mobile robots act are introduced. Collision avoidance with dynamic path planning according to the complexity of situations is also discussed. Then, a method for collision avoidance based on rules and negotiation by communication is presented. Finally, this method is applied to a developed prototype system including two mobile robots, and as a result of experiments operating real robots, it is concluded that this method is valid.

1. INTRODUCTION

Aiming at robotization of high level tasks such as maintenance tasks in nuclear power plants, we are developing an autonomous and decentralized robot system, ACTRESS (ACTor-based Robots and Equipments Synthetic System)[1], which is designed based on a concept of functional distribution and cooperation. ACTRESS is a robot system which is composed of multiple robotic agents and a communication network between them. Any types of autonomous robots, computing systems, and equipments can be defined as robotic agents called *robotors*.

In the previous studies on ACTRESS, communication framework was designed[2], and a wireless communication system for message exchange between *robotors* was developed[3]. Using the communication system, a method for task assignment in decentralized system was also developed[1]. Moreover, evaluating the communication amount by simulation[4], the optimal functional distribution for environment management was derived[5]. In this paper, collision avoidance with dynamic path planning among multiple autonomous mobile robots is focussed as a part of ACTRESS research activities.

Path planning problem is one of typical subjects which should be treated in robotics field related to mobile robots. For the purpose of coordination of multiple robots coordination, problem solving on motion planning was discussed[6], and a framework for integrating multiple robots coordination was proposed[7]. In these approaches, centralized strategy for solving planning problems was adopted. However, in the decentralized robot system expecting the autonomy of every robots, application of distributed problem solving techniques is required. Concerning related studies, contract net framework has been proposed[8]. In addition, as a concrete application, a communication system for cooperative motion of multiple mobile robots which move in a road-like environment was developed[9]. However, methods of collision avoidance for actual multiple mobile robots in a free environment have not been developed. On the other hand, though methods for collision avoidance among multiple mobile robots have been reported[10], these methods are implemented only on simulation, and lack of discussions about sensing other robots' motions, notifying other robots of intention on robots' behavior, and solving deadlock situations. The objective of this paper is to develop a generalized method for collision avoidance for an autonomous mobile robot among multiple robots, based on discussions of a proper approach for collision avoidance taking account of various deadlock situations.

2. STRATEGY FOR PATH PLANNING

2.1 Basic Strategy

Functional distribution for management of environmental information has been discussed, and it was concluded that strategy of the centralized global environment management and the local environment model constructed in each *robotor* is most efficient as a result of evaluation of communication amount of information exchange between multiple *robotors*[5]. The local environment model must be referred when each mobile robot plan paths.

Concerning path planning strategy, combination of a static planning process and dynamic planning processes was adopted. The flow of path planning is shown in Fig. 1. Initial plan is derived by static path planning based on local environment model, and can be modified by dynamic path planning depending on collision situation during locomotion. With regard to static path planning, an efficient algorithm is reported[11]. Dynamic path planning includes collision avoidance between mobile robots, replanning of the initial plan, and problem solving for deadlock situations. This process is characterized by utilization of not only sensor data but also information acquired by communication.

2.2 Deadlock Solution in Path Planning Problem

Various situations can be imagined in dynamically changing environment. The complexity of the situations causes the deadlocks for mobile robots. Deadlock is a state that some mobile robots cannot proceed with their motion to achieve the given target. We propose a multi-level path planning strategy as shown in Table 1. In an environment where only static obstacles exist, the required motion can be achieved only by static path planning (obstacle avoidance). In case that multiple mobile robots act autonomously in an environment, however, the collisions between robots possibly occur. It is not preferable to predict the collisions in the decentralized robot system, because prediction requires management of all the actions of each robots. Therefore, the path avoiding the other mobile robots should be planned dynamically with solving deadlocks. The hierarchy of Table 1 is defined according to the complexity of the deadlocks.

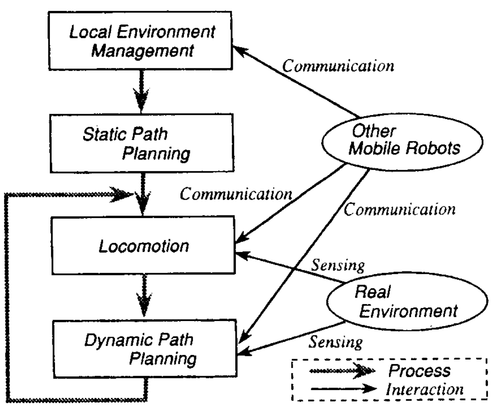

Fig. 1 Flow of path planning process

Collision avoidance based on such a local algorithm as the potential method is applicable only in limited cases. In simple situations, it is effective to follow predefined traffic rules, or to give way based on priority of tasks. Nevertheless, in situations where a deadlock occurs, it is demanded to determine a leader among the robots, who solve the deadlock and plan the actions of all the robots involved in the deadlock. However, in more complicated situations where any leaders cannot solve the deadlocks, specialized deadlock solvers according to complexity of the situations should be provided for the robot system. The ultimate deadlock solver may be a human operator, namely human interface system which can transmit instructions from the human operator to mobile robots.

In order to realize this deadlock solving function, it is a serious problem to incorporate into each robots a mechanism to detect the deadlock, select the proper method to solve the deadlock judging the complexity of the situations, and communicate with the certain deadlock solver. Concerning the utilities in path planning, the performance of path planning depends on the sensing ability in the lower levels, but in higher level, the communication plays important role for path planning with deadlock solving, because many processes for negotiation, information exchange, reporting, and instructions are expected to be necessary.

Table 1 Multi-level path planning strategy

Difficulty of Situation	Method for Path Planning		Problem Solver for Path Planner	Utilities
High	Dynamic Path Planning	*Problem Solving by A Human Operator*	*Human*	*Communication*
		Problem Solving by A High-Level Deadlock Solver	*Deadlock solver*	
		:		
		Problem Solving by A Low-level Deadlock Solver		
		Path Planning by A Robot Leader	*Mobile Robot*	
		Giving Way Based on Priority of Tasks		
		Collision Avoidance Based on Mobile Rules		
Low		*Collision Avoidance Based on Local Algorithm*		
	Static Path Planning			*Sensing*

2.3 Representation of Situation

In dynamic path planning, a deadlock solver should know the situations of each robots, which is informed of by communication. As information representing the situations, the following factors are essential for deadlock solving:

(1) **Task Requirement**: A robots which move with executing a task has less degrees of freedom to avoid collisions. The degrees of freedom depends on contents of the objective task. On the other hand, the robot which are executing an emergency task has priority to go ahead.

(2) **Environment**: The local environment around the robot restricts its mobility. The robot who are surrounded by many obstacles or robots have less chances to escape the situation.

(3) **Robot Performance**: Assuming multiple mobile robots with different features, the ability to avoid collisions depends on their performance. It's effective for a smart and dextrous robot to carry on avoiding actions.

3. METHOD FOR COLLISION AVOIDANCE

3.1 Algorithm for Collision Avoidance

Focusing on two levels in dynamic path planning discussed in 2.2, we propose methods for collision avoidance based on rules and communication depending on the complexity of the situations. The abstract flow of collision avoidance is shown in Fig. 2. At first, mobile robots try to apply rules to avoid collisions without communication. If any rules cannot be applied because of the situation or environmental restriction, the mobile robots stop and start communication for negotiating the way to avoid deadlocks.

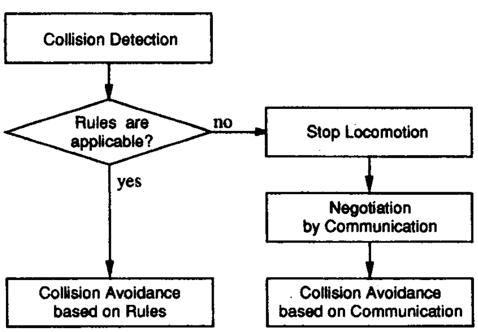

Fig. 2 Flow of collision avoidance

3.2 Collision Avoidance Based on Rules

Rules are provided for switching the algorithms for motion planning according to the situations. The rules corresponds to the sensing ability of mobile robots. Assuming that each robot has ability to detect collisions and measure the distance to a colliding robot and its velocity in the forward direction of the avoiding robot, the following two rules are described. In these rules, the robot can know the location of the colliding robot by using sensors for detecting collisions, and judge whether it is approaching or leaving by measuring its velocity.

1. If [the colliding robot locates front and near]
   and [it is approaching],
   then [avoid from the left].
2. If [the colliding robot locates front and near]
   and [it is leaving],
   then [stop locomotion for a while].

3.3 Collision Avoidance by Negotiation

Each robot can choose the proper method for collision avoidance based on environmental information which is acquired from an environment manager by communication. In case that rules are not applicable because of existence of obstacles, the robot start negotiation for giving way to each other. Negotiation is executed after both robots stop locomotion recognizing the possibility to collide each other.

Figure 3 shows a typical example of negotiation processes, where arrows denote message transfers by communication. During the message exchange of warning and its reply, priorities of each robots are reported to each other. In the case of Fig. 3, Mobile Robot 1 (MR 1) detects the collision, and taking account of the priorities, it determines MR 1 is reasonable to avoid collisions due to high priority. If Mobile Robot 2 (MR 2) detects the collision, the reverse processes are executed. If the priority of MR 2 is found to be higher than MR 1 as a result of negotiation, MR 1 sends to MR 2 a declaration to stay in stead of a command to stay. Then, MR 2 moves to avoid collision and sends a command to restart to MR 1.

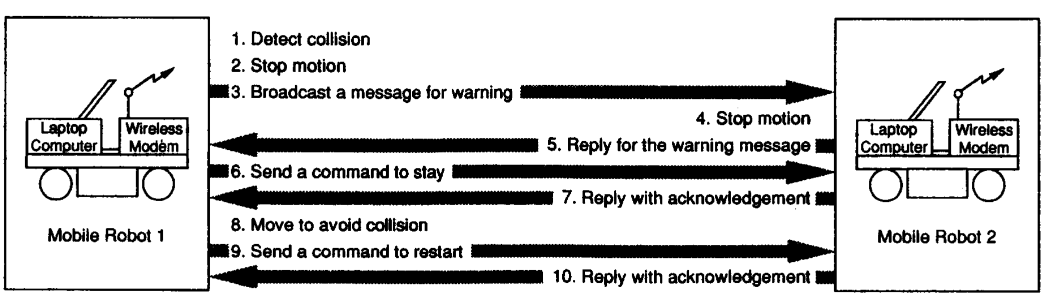

Fig. 3 Process of collision avoidance by negotiation

4. EXPERIMENTS OF COLLISION AVOIDANCE

4.1 Configuration of Prototype System

A prototype system of the decentralized robot system has been developed, which is composed of two autonomous mobile robots, a personal computer for a human interface, and another personal computer for a global environment manager. The trigger to start motion is sent from the human interface. The global environment manager is dedicated to manage and service of environmental information (a map). The configuration of the prototype system is shown in Fig. 4. Every computer including laptop computer on mobile robots is equipped with a wireless modem. Negotiation and any other types of communication between *robotors* are preformed using the wireless communication system[3].

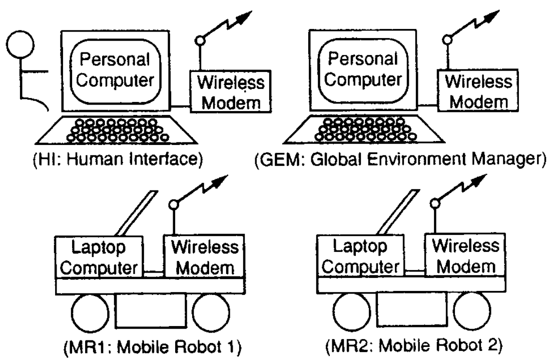

Fig. 4 Configuration of the prototyped robot system

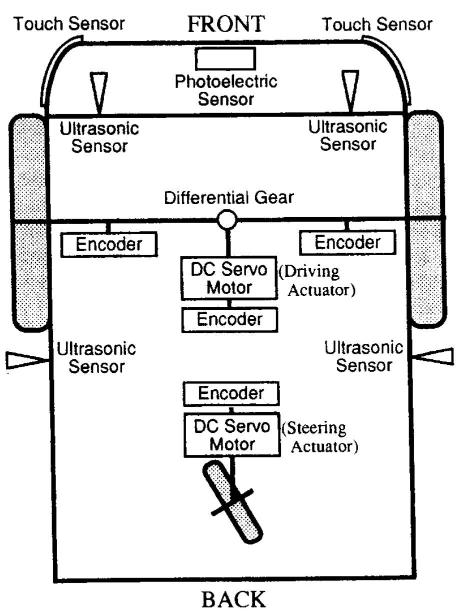

Fig. 5 Structure of the mobile robot

Each mobile robot is an autonomous steering type robots with three wheels, whose structure is illustrated in Fig. 5. In order to avoid the interference between active sensors of different robots, every robot has to utilize different methods for collision detection and locomotion control. In the prototype system, MR 1 detects collisions using a photoelectric sensor, and its locomotion is controlled by means of dead reckoning based on signals from encorders installed at each driving wheels. MR 2 detects collisions using ultrasonic sensors, and its locomotion is navigated along a wall with measuring the distance to the wall by ultrasonic sensors. Figure 6 shows a photo of the two mobile robots.

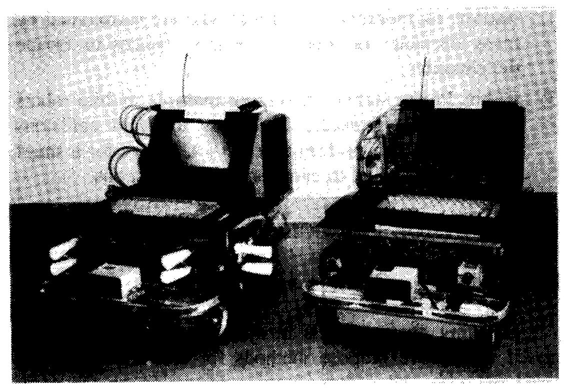

Fig. 6 Photo of two mobile robots

Table 2 Priority points concerning task requirements

Motion Conditions	Ct
Under movement in an emergency state	5
Under movement	2
Under movement with executing a task	0

Table 3 Priority points concerning environment

Environmental Situation	Ce
Avoiding action is permitted	10
Avoiding action is constrained	0

Table 4 Priority points concerning robot performance

Locomotion type	Cp
Spin type	2
Steering type (with a small turn)	1
Steering type (with a large turn)	0

4.2 Definition of Priority

Priority of robots has a significant meaning for deadlock solving in path planning. In order to determine the priority quantitatively, priority points on each factors discussed in 2.3 are defined for the case study using the prototype system. Table 2 shows priority points concerning task requirements (Ct). In the same manner, priority point concerning environment (Ce) and robot performance (Cp) are valued as shown in Table 3 and Table 4 respectively. The total priority point (C) is calculated as a sum of individual priority points:

$$C = Ct + Ce + Cp$$

C is a generalized index which represents how movable the robot is in the situation, and how much requirement is imposed on the robot. The robot with high points should carry out avoiding motion. The total priority point is informed of during negotiation for dynamic path planning, which is described in *control field* of the *message protocol core*[2].

4.3 Experimental Results

Three typical test cases of collision avoidance were taken up for the prototype system. As an example applying Rule 1, a case as illustrated in Fig. 7 was experimented, that two mobile robots approach each other from the front. As a result of real robots operation, the trajectories of two robots were obtained as illustrated in Fig. 8.

As an example applying Rule 2, a case as illustrated in Fig. 9 was experimented, that a mobile robot catches up to another robot from the back. The trajectories of two robots were obtained as illustrated in Fig. 10. In this figure, a robot stops locomotion at the black painted location.

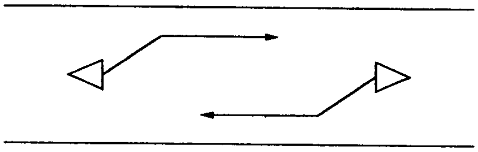

Fig. 7 Test case 1

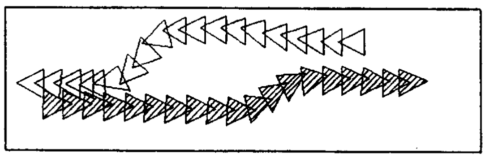

Fig. 8 Experimental result of test case 1

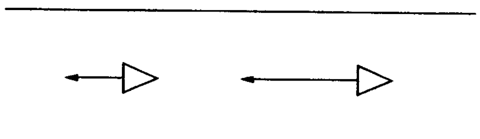

Fig. 9 Test case 2

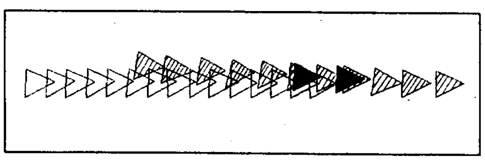

Fig. 10 Experimental result of test case 2

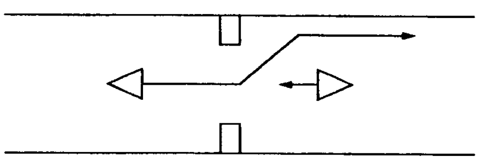

Fig. 11 Test case 3

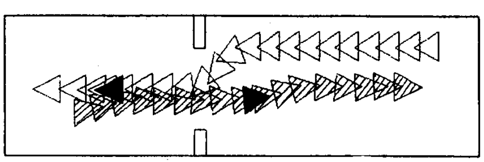

Fig. 12 Experimental result of test case 3

```
Send Message(1).
TO      :****
FROM    :MR-1
CONTROL :13                I
CLASS   :CR
TYPE    :COO
Message :I need Obstacle avoidance.
Now Time:Wed Mar 27 15:52:31 1991

Receive Message(1).
TO      :MR-1
FROM    :MR-2
CONTROL :12
CLASS   :CR
TYPE    :COO
Message :Ok.
Now Time:Wed Mar 27 15:52:33 1991

Send Message(2).
TO      :MR-2
FROM    :MR-1
CONTROL :13                III
CLASS   :CR
TYPE    :COO
Message :Stop.
Now Time:Wed Mar 27 15:52:33 1991

Receive Message(2).
TO      :MR-1
FROM    :MR-2
CONTROL :12
CLASS   :CR
TYPE    :COO
Message :Ok.
Now Time:Wed Mar 27 15:52:35 1991

Send Message(3).
TO      :MR-2
FROM    :MR-1
CONTROL :13                V
CLASS   :CR
TYPE    :OFR
Message :Go.
Now Time:Wed Mar 27 15:53:15 1991

(A) Mobile Robot 1
```

```
Receive Message(1).
TO      :****
FROM    :MR-1
CONTROL :13
CLASS   :CR
TYPE    :COO
Message :I need Obstacle avoidance.
Now Time:Wed Mar 27 15:52:18 1991

Send Message(1).
TO      :MR-1
FROM    :MR-2
CONTROL :12                II
CLASS   :CR
TYPE    :COO
Message :Ok.
Now Time:Wed Mar 27 15:52:18 1991

Receive Message(2).
TO      :MR-2
FROM    :MR-1
CONTROL :13
CLASS   :CR
TYPE    :COO
Message :Stop.
Now Time:Wed Mar 27 15:52:20 1991

Send Message(2).
TO      :MR-1
FROM    :MR-2
CONTROL :12                IV
CLASS   :CR
TYPE    :COO
Message :Ok.
Now Time:Wed Mar 27 15:52:20 1991

Receive Message(3).
TO      :MR-2
FROM    :MR-1
CONTROL :13
CLASS   :CR
TYPE    :OFR
Message :Go.
Now Time:Wed Mar 27 15:53:00 1991

(B) Mobile Robot 2
```

Fig. 13 Communication log during collision avoidance

Moreover, as an example using communication, a case as illustrated in Fig. 11 was experimented, that two mobile robots approach each other from the front but the rules cannot be applied because obstacles exist. The trajectories of two robots was obtained as illustrated in Fig. 12, where both robots stop locomotion at the black painted position, and communicate with each other for negotiation.

The communication log during collision avoidance is printed in Fig. 13 where the left side shows the sent and received messages of MR 1 and the right side shows the ones of MR 2. In this figure, each message is described in the format of the *message protocol core*. The contents of message are:

Message I:	Warning broadcast
Message II:	Reply for the warning
Message III:	Command to stay
Message IV:	Acknowledgement for command
Message V:	Command to restart

In this communication, the priorities of the robots described in the *control field* was determined as follows:

MR 1: C = 13 (Ct = 2, Ce = 10, Cp = 1)

MR 2: C = 12 (Ct = 2, Ce = 10, Cp = 0)

The results of experiments prove that the low level deadlock can be solved with this method. This verifies the effective performance of this method.

5. CONCLUSION

In an autonomous and decentralized robot system including multiple autonomous mobile robots, strategy for path planning was addressed. Concerning dynamic path planning in case that any collisions between mobile robots may occur, a multi-level scheme for deadlock solving according to the complexity of situations was proposed, and representation of priority of robots was discussed. Then, a method for collision avoidance based on rules and negotiation by communication was presented. Finally, this method was applied to a prototype system including two mobile robots, introducing detail definition of priority points. As a result of experimental operations, the validity of the method was proved.

By substantiating rules with improving sensing ability of mobile robots, and by implementation of negotiating function with supposing various situations, the proposed method can be extended and expected to deal with more general and complicated deadlocks.

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