Paper:

Collision Avoidance Using Communication between Autonomous Mobile Robots

Koichi Ozaki* , Hajime Asama** , Yoshiki Ishida*** , Akihiro Matsumoto**** , and Isao Endo**

* Facurity of Engineering , Utsunomiya University, 2753 Ishii-cho, Utsunomiya, Tochigi, 321, Japan
** The Institute of Physical and Chemical Research (RIKEN), 2-1, Hirosawa, Wako, Saitama, 351-01, Japan
*** Computer Center , Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka, 812, Japan
**** Faculty of Enginerring, Toyo University, 2100, Nakanodai, Kujirai, Kawagoe, Saitama, 350, Japan
[Received June 13, 1996; accepted July 10, 1996]

This paper addresses mutual collision avoidance between multiple mobile robots based on a layered strategy. In this Strategy , static motion generation and dynamic motion generation of several levels are provided , and a proper level of dynamic motion generation is selected for mutual collision avoidance according to the complexity of the situation. We have implemented two typical methods in the layered strategy , which are rules-based local collision avoidance and negotiation-based global one using communication. In each method, a robot detects collision and applies as a local method as possible. Experimental results show two actual mobile robots can achieve mutual collision avoidance based on the layered strategy.

Keywords: Multiple mobile robots, Collision avoidance, Communication, Traffic rule, Negotiation

1. Introduction

Systems composed of multiple autonomic mobile robots and studies on their mutual cooperation[1] have been attracting attention recently. In these systems, flexibility and robustness are expected to be realized through mutually cooperative robot activities. By now, in our research and development, we have been trying to achieve the distributed autonomous robotic system ACTRESS,[2] in which necessary functions are distributed to multiple agents. ACTRESS is composed of multiple robots, including mobile robots, and multiple autonomic agents such as computers. Each agent is equipped with a communication function. We classify multiple robot activities into 1) individual action: each robot individually actives in parallel; and 2) collaborating action: each robot acts mutually in cooperation with the other. This paper discusses collision avoidance between mobile robots, as an example of the individual action.

Path planning for collision avoidance amid moving obstacles has been proposed.[3-6] These paper have discussed on only simulation, yet the discussion has not sufficiently done on how the robot actually acquires necessary information for planning. Regarding actual collision avoidance by actual mobile, these paper propose methods that determine collision avoidance activities based on sensor information.[7,8] These methods thus acquire only local information from sensors. Therefore, deadlock is predicted in complicated situations and no information will be exchanged with mobile collision obstacles. Yuta et al. proposed the modest cooperation and experimented with robots that offer ways to mutually avoid collision[9]. In this experiment, mobile robots must recognize situations by communication whenever they move. Therefore, communication processing loads increase remarkably with the number of robots. Kato et al. realized collision avoidance by applying traffic rules[10]. However, rule conditions must be judged through sensor information only and supplementary rules must be prepared based on environmental conditions.

This paper proposes a layered collision avoidance strategy with multiple methods, considering actual application to mobile robots. This strategy efficiently performs collision avoidance with the local method in simple situations and with the global method in complex situations using communication. This study develops two methods applying rules and communication based on this strategy and conducts a collision avoidance experiment with actual mobile robots.

2. Collision Avoidance Strategy Between Mobile Robots

2.1. Strategy by Static Motion Generation and Dynamic Motion Generation

In this paper, we define two types of information. One is dynamic environmental information (position, posture, and speed) for mobile elements such as mobile robots. The other is static environmental information in geography about static elements such as walls and obstacles. A mobile robot must be to acquire environmental information when it plans a path to a goal. It is difficult that constant comprehension of dynamic environmental information in an environment where multiple robots move. Dynamic environment information is thus beyond the scope of this study and only static

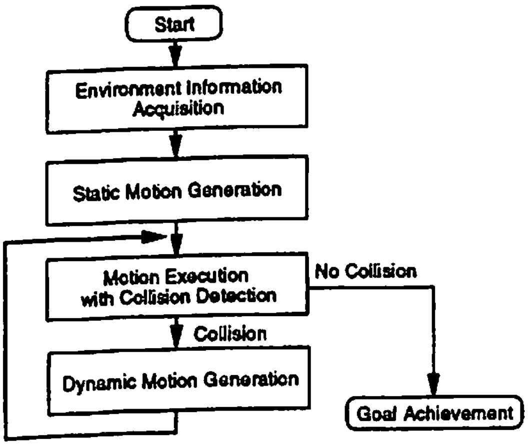

Fig. 1. Processing flow of motion generation.

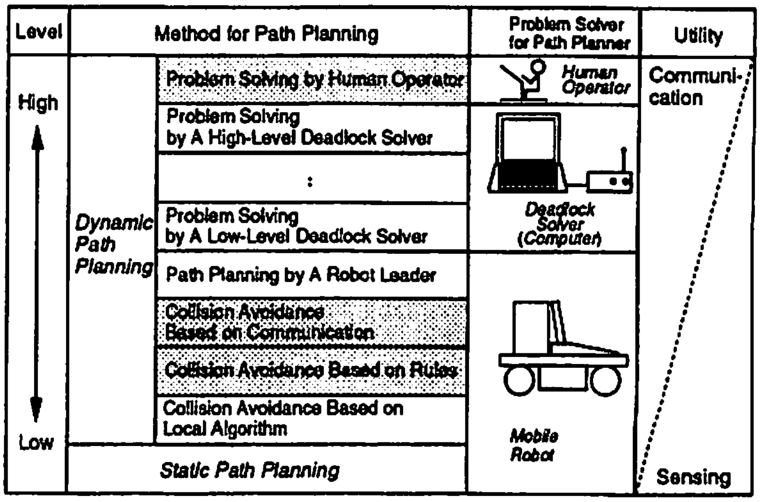

Fig. 2. Layered strategy for collision avoidance.

rmation is dealt with[2].

In the processing flow of motion generation (**Fig.1**), a robot first plans a path and generates motion based only on static environment information (static motion generation). It then, moves, detecting the possibility of collision (collision detection), and generates collision avoidance motion based on dynamic environment information whenever collision detection is made (dynamic motion generation).

2.2. Functions of Sensing and Communication

Common sensors have a local detection area compared to communication and can be utilized with low load. Reliable information cannot be obtained outside the detection area, however, because detection objects are assumed. Adding to this, mobile robots have limits in power requirements and processing abilities, which restrict the sensors installed. Thus, only poor information is obtained.

Information through communication is conveyed as messages, on such occasions as reporting situations of a robot. In other words, the information has high reliability, since it is clarified by the robot. Thus, it is possible to convey mach information by preparing communication protocols. However, communication has a wide range information communication area, because of which the communication processing load rises as the number of agents increases in the system.

2.3. Layered Motion Generation Strategy In Collision Avoidance

Problems of collision exist in the environment where multiple mobile robots move. Simple problems are preferably solved with local information exchange as far as possible, when considering the efficiency of the total system. However, complicated problems must be solved with more global conditional comprehension, since the local information processing alone can not cope with every situations.

Thus, this paper prepares plural collision avoidance methods depending on the complexity of the problems and abilities of the robots, to cope with even complicated problems keeping the efficiency of the system. The methods are hierarchically structured to be used appropriately. Summarized below are the requirements in collision avoidance.

(1) Preparing plural collision avoidance methods to cope with various problems

(2) Solving problems locally and dispersedly as far as possible

In view of the above, we propose a layered motion generation strategy for collision avoidance (**Fig.2**), based on "Concentration - Distribution," "Global - Local." Figure 2 hierarchically expresses the methods prepared for solving complicated problems. This strategy is composed of static and dynamic motion generation. In static motion generation, general path planning methods are applicable. In dynamic motion generation, a robot adopts a low-level method first. Then, if consecutive movement cannot be continued with this method, the robot increases the level by one and generates motion-gathering information more globally. In this strategy, concerned robots facing collision solve the encountered problems with each other. As the level increases, a concentrated agent that solves the deadlock performs problem solving in a global manner. Human intervention is also considered to be the final method. Important, however, is the role of communication between agents as the level increases.

At the level where mobile robots can cope with problems, collision avoidance based on a local algorithm is the lowest level, an example of which is reflex motion based on sensor information. At the next level, motion generation is made based on rules. The robot recognizes situations with sensing and avoids collision by applying the appropriate rule. If the rule is not applicable, collision avoidance is executed based on communication between robots. By applying communication, the robot can acquire information about a close-to-collision opponent, place, speed, and path. Then, the robot can determine collision avoidance motion by negotiating with the opponent. At the next level in these steps, a certain robot, as a leader, collects information widely and generates motion for collision avoidance, and instructs the robots concerned.

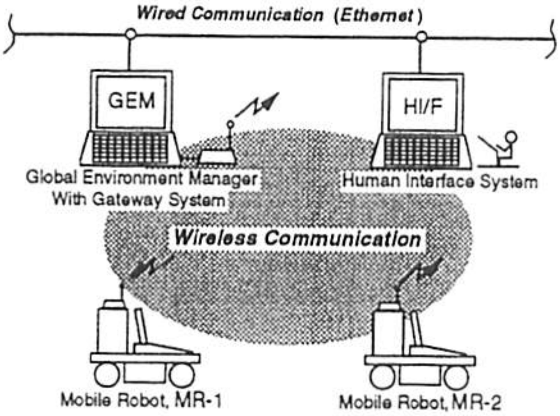

Fig. 3. Configuration of prototyped robot system.

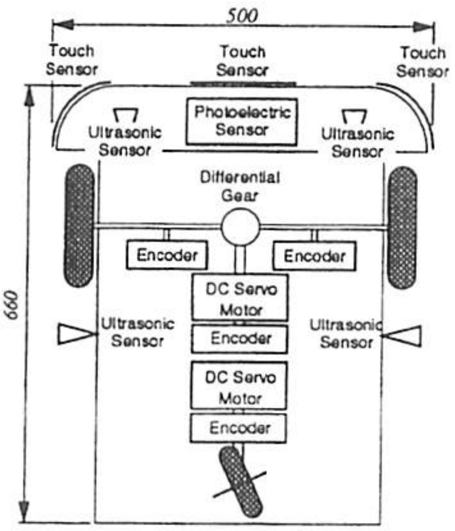

Fig. 4. Structure of mobile robot.

3. Construction and Experiment of Collision Avoidance Methods

3.1. Configuration of Prototype System

We have developed a prototype system of the ACTRESS.[2] We have constructed the collision avoidance method using a part of the system. **Figure 3** illustrates its configuration and is composed of two autonomous mobile robots (MR-1 and MR-2), a global environment management computer (Global Environment Manager: GEM), and a human interface computer (Human Interface System: HI/F). The mobile robot is equipped with a radio communication system, while GEM has the role of gateway to interface wireless communication with wired communication (Ethernet)[11].

Two mobile robots are a type of 3-wheel steering robot. The mobile robot is equipped with a lap-top personal computer (J-3100GL/CPU: 80286/287/12 MHz), with which driving control is managed and communication is enabled through a wireless modem connected to the serial interface (RS-232C) of the computer. The effective baud rate is about 2000 bps. **Figure 4** illustrates the structure of the mobile robot. This robot moves with two driving wheels and one steering wheel controlled by 2-axis servomotors. The robot has an encoder for position detection each at the left and right axes of the driving wheels, two ultrasonic sensors at the front and one each at the left and right sides as out-view sensors, one photoelectric sensor for proximity detection, and three touch sensors for collision detection.

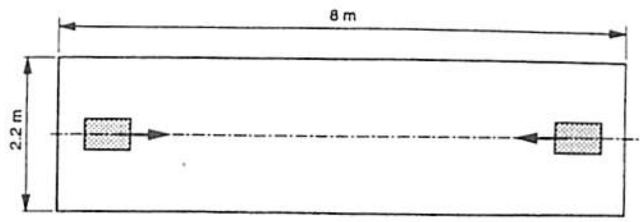

Fig. 5. Experimental environment.

GEM manages static environment information (maps) and presents it on demand from the mobile robot. The HI/F is a system that performs communication between humans and mobile robots, examples of which include a motion activation sign and motion order at the time of deadlock.

3.2. Experimental Environment and Control of Mobile Robots

This paper premises the realization of autonomous movement by plural mobile robots in an indoor environment. Therefore, we have developed collision avoidance methods aimed at corridor environment. **Figure 5** illustrates the experimental environment. Described below are the premised experimental conditions. Each robot is placed at the center of the corridor and is given the goal with the relative coordinates of the robots. The goal of each robot is seven meters ahead. Information about the other robot's path of movement is not given. For the out-view sensors, the MR-1 utilizes a photoelectric sensor that can cover wide and narrow two-space detection, while the MR-2 utilizes an ultrasonic sensor, to prevent erroneous operation caused by interference between the output signals from sensors. For movement control, the MR-1 moves based on deadreckoning, rotating angles of the left and right driving wheels via the encoders, while the MR-2 performs navigation with along-the-wall movement by the ultrasonic sensor[12]. The speed of each robot is 7 cm/s.

3.3. Construction of Collision Avoidance Methods Based on Dynamic Motion Generation Strategy

The mobile robot acquires static environment information from GEM when receiving an instruction about the goal and operation start ordered by the HI/F. Based on this information, the robot plans a path to the goal and starts to move. If collision detection is recognized, the appropriate collision avoidance method is applied based on the layered motion generation strategy. In the layered motion generation strategy, collision avoidance methods proposed include, for example, the virtual impedance method[3] for local application and the Fujimura method[4] for concentrated application. In this study, two collision avoidance methods are constructed whose level corresponds to the middle of the above proposed methods and to the layer shaded in Fig.2. One of the constructed methods is a "method based on

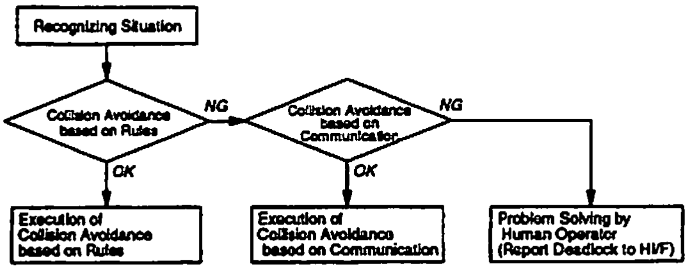

Fig. 6. Processing flow for collison avoidance strategy.

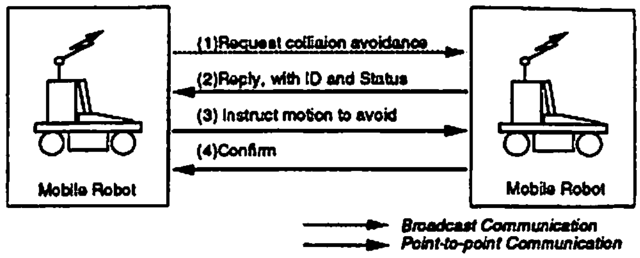

Fig. 9. Communication procedure of negotiation for collision avoidance.

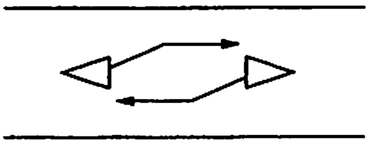

Fig. 7. Rule 1.

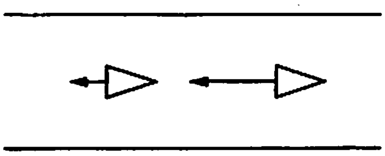

Fig. 8. Rule 2.

rules" and the other is a "method based on communication." In addition, to encounter the case where these two methods cannot solve problems, "problem solving with a human operator" is also prepared as the highest level and most concentrated method. In problem solving with a human operator, situations are reported to the HI/F using communication. **Figure 6** shows the low-to-high-layer priority processing flow with each method.

3.3.1. Collision Avoidance Based on Rules

In this experiment, the following rules are constructed, not considering collision from the sides because a corridor environment is presumed.

(1) Rule 1: Left avoidance motion rule (Fig.7)

if {Opponent's position = Frontal proximity and Opponent's speed = Reverse direction and Enough space for avoidance motion}

then {Taking left avoidance path}

(2) Rule 2: Instantaneous stop rule (Fig.8)

If {opponent's position = Frontal proximity and Opponent's speed = Same direction}

then {Instantaneous stop}

In order to apply these rules, the MR-1 measures the frontal robot's position and speed based on chronological change in detection with the wide and narrow range photoelectric sensors. The MR-2 measures the frontal robot's position and speed based on chronological measured values with the ultrasonic sensors. Conditions of the opponent's position and speed can be determined with these measured values.

In the left avoidance motion rule, an avoidance motion control pattern is given preliminarily to the robot. With this control pattern, the robot changes the direction of movement 45 degrees toward the left by steering the driving wheels, then the robot changes the direction again toward the right to move toward the front by steering the driving wheels. In order to avoid collision using this motion control pattern, a space of 120 cm for the front and 80 cm for the left is required on detection of the collision. This space is calculated experimentally. The robot can determine the presence of this avoidance area (no presence of obstacles), because of the given preliminary environment information (map) from GEM.

If no rules are applicable, the robot renounces the collision avoidance method based on rules, and tries to apply the one layer ahead collision avoidance method based on communication.

3.3.2. Collision Avoidance Method Based on Communication

Obstacles are placed in the corridor to create a condition where no rules can be applied. The obstacles are positioned so as to come into contact with the wall between two robots. Fig. 12 illustrates the environment. The robots can determine no rules are applicable in this environment, since the measurements and locations of the obstacles are given preliminarily.

In the obstacle avoidance method based on communication, the robot stops first and communicates that collision detection is sensed, then specifies the opponent robot (robot's ID recognition). After that, the robots negotiate each other about which robot should avoid collision first and determine it.

In this communication, the Message Protocol Core[2] is adopted as the framework for negotiation. The communication procedure of negotiation is described below.

(1) If collision detection is sensed with the front sensors, the robot broadcasts a warning of collision.

(2) There are only two robots in this experiment. Thus, either robot that receives the warning can determine that the opponent robot facing collision is itself. The robot that receives the warning stops and replies with its ID and status (priority).

(3) The robot that receives this reply determines which robot should avoid collision first considering mutual status, and instructs avoidance motion.

Table 1. Priority points concerning environment.

Environmental situation	*Ce*
Avoiding action is not constrained	10
Avoiding action is constrained	0

Table 2. Priority points concerning task requirements.

Motion conditions	*Ct*
Movement in an emergency state	5
Movement without task execution	2
Movement with task execution	0

Table 3. 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

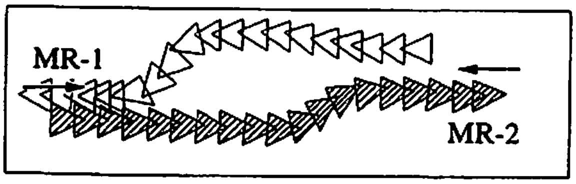

Fig. 10. Experimental result of collision avoidance using rule 1.

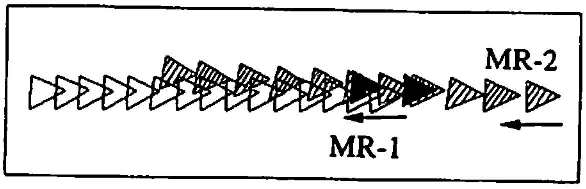

Fig. 11. Experimental result of collision avoidance using rule 2.

(4) The robot that receives this instruction confirms the instruction.

We define priority points to determine such motion to avoid. One of the mobile robots that has the priority passes first after negotiation and comparison of priority points. The following must be considered when defining priority points.

(1) Priority points concerning the environment C_e: This indicates space for avoidance motion. If the space is occupied by obstacles, the robot cannot avoid collision there. Therefore, the priority points C_e, where avoidance is possible, are set to extremely high values. In contrast, the priority points C_e, where avoidance is not possible, are set to extremely low values.

(2) Priority points concerning task requirements C_t: This indicates priority points on task contents. An emergency task has the highest priority points C_t. In other cases, a robot that is free of tasks has priority, because avoidance motion can be executed more easily than the other in-task-processing robot.

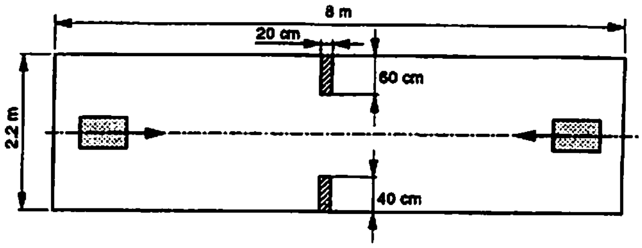

Fig. 12. Experimental environment within obstacles.

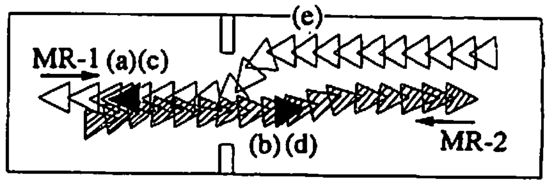

Fig. 13. Experimental result of collision avoidance using negotiation.

(3) Priority points concerning robot performance C_p: This indicates performance grades of robots. It is effective to have the high-performance robot executes collision avoidance. Thus, the high-performance robot has higher priority points C_p than the others.

In this experiment, we arrange these priority points in tables: **Table 1** for priority points C_e, **Table 2** for priority points C_t, and **Table 3** for priority points C_p. Considering the above discussion, we intentionally preset the relations between these priority points as shown below.

$$C_e > C_t > C_p$$

The total priority points C is formulated as shown below.

$$C = C_e + C_t + C_p$$

If negotiation fails and the collision avoidance method based on communication cannot be applied, its status is reported to the HI/F.

3.4. Experiment with collision Avoidance Method Based on Dynamic Motion Generation Strategy

3.4.1. Experimental Results In Collision Avoidance Based On Rules

Figure 10 and **Fig.11** show traces of robots in the experiment of collision avoidance based on rules. Each apex of a triangle indicates ground-wheel contact points, a white triangle refers to the MR-1, a shaded the MR-2, and a black indicates stop. The position of the robot is recorded at an interval of five seconds and an arrow indicates the robot's direction of movement. In Fig.10, two robots mutually avoid collision applying the left avoidance motion rule after detecting the front robot as each other. In Fig.11, the MR-2 applies the instantaneous stop rule when detecting the MR-1, which moves in the same direction and mutually avoid collision.

```
------------------------
To      : ****
From    : MR-1
Control : 13
Class   : CORE           (a)
Type    : NEGOTIATION
Message : REQUEST.AVOID
Time    : 15:52:32
------------------------
To      : MR-1
From    : MR-2
Control : 12
Class   : CORE           (b)
Type    : NEGOTIATION
Message : ACCEPT
Time    : 15:52:33
------------------------
To      : MR-2
From    : MR-1
Control : 13
Class   : CORE           (c)
Type    : NEGOTIATION
Message : REQUEST.STOP
Time    : 15:52:33
------------------------
To      : MR-1
From    : MR-2
Control : 12
Class   : CORE           (d)
Type    : NEGOTIATION
Message : ACCEPT
Time    : 15:52:35
------------------------
To      : MR-2
From    : MR-1
Control : 3
Class   : CORE           (e)
Type    : NEGOTIATION
Message : RESTART
Time    : 15:53:15
------------------------
```

Fig. 14. List of communication (Negotiation) log.

3.. Experimental Results of Collision Avoidance Based on Communication

This collision avoidance is experimented with under the conditions shown in **Fig.12**, provided that the robot's performance priority points of the sharp-turning MR-1 are to be $C_p = 1$ and the dull-turning MR-2 $C_p = 0$. These two robots are presumed to be free from work (merely moving) conditions, and the priority points concerning work are set to $C_t = 2$. **Figure 13** shows the robots' traces in this experiment and **Fig.14** is the communication log (negotiation record).

We use letters in Figs.13 and 14 to clarify each corresponding position and communication of the mobile robots. In this experiment, the MR-1 detects collision first, and stops, then makes communication of a warning of collision. In communication (a), no opponent robots are specified. Thus, the warning is sent to another robot by broadcast (To field) is (****). In communication (b), the MR-2 accepts the MR-1's request of collision avoidance made by communication (a), recognizing the possibility of collision. The robot's priority points are recorded on the Control field, with which MR-1 and MR-2 can recognize the priority points of each other. In this experiment, both robots are in a difficult situation to avoid a collision, keeping the record of $C_e = 10$. For this reason, priority points of MR-1 is $C = 13$ and MR-2 $C = 12$. Thus, in this experiment, MR-1 takes the avoidance motion first. MR-1 requests the MR-2 to stop (communication (c)) and performs collision avoidance when receiving acceptance (communication (d)). After the completion of collision avoidance, MR-1 instructs MR-2 to resume movement (communication (e)). **Figure 15** is a photograph showing this status.

The above experimental results show that even the unsolved collision avoidance with the rules can be solved by using communication. Further, by considering such priority points as "Environmental situation," "Task requirements," and "Robot performance," avoidance that can cope with a variety of conditions is enabled.

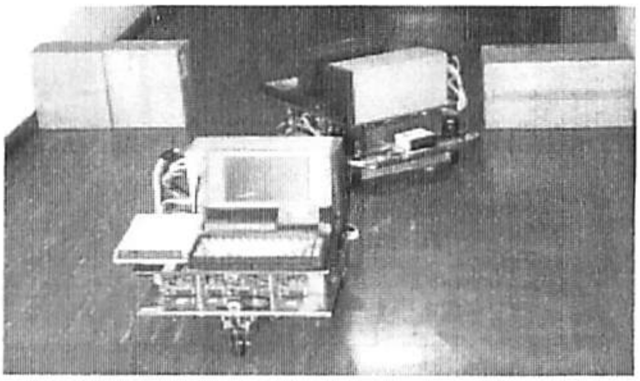

Fig. 15. Photograph of collision avoidance using negotiation.

4. Conclusion

This paper proposes the layered motion generation strategy to efficiently perform mutual collision avoidance in actual mobile robots. Based on this strategy, we have developed collision avoidance methods based on rules and communication. Further, we have experimented with these collision avoidance by methods using two mobile robots, constructing the operation algorithms on them. These two robots realized collision avoidance selecting each of these two motion generation methods according to the situation. We are planning to study in more detail how to express priority points quantitatively.

In this paper, we applied the proposed methods to only two robots. This strategy, however, may be applicable to collision avoidance between multiple robots by using other sensors that prevent interference. In addition, the identification of opponent robots in collision avoidance may be enabled by exchanging information on parameters such as positions with one another.

References:

1) H. Asama: "Cooperative Motion and Swarm Intelligence by Multiple Mobile Robots," Journal of the Society of Instrument and Control Engineers, **31**-11, 1155-1161, 1992.
2) Y. Ishida, H. Asama, K. Ozaki, A. Matsumoto, I. Endo: "Design of Communication System and Development of a Simulator for an Autonomous and Decentralized Robot System," Journal of the Robotics Society of Japan, **10**-4, 544-551, 1992.
3) T. Arai and J. Ota: "Motion Planning of Multiple Mobile Robots," Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, 1761-1768, 1992.
4) K. Fujimura: "Route Planning for Mobile Robots Amidst Moving Obstacles," Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and systems, 433-438, 1992.
5) T. Tsubouchi, T. Naniwa and S. Arimoto: "Planning and Navigation by a Mobile Robot in the Present of Multiple Moving Obstacle and Their Velocities," Journal of the Robotics Society of Japan, **12**-7, 1029-1037, 1994.
6) H. Noborio and T. Yoshioka: "On a Deadlock-Free Characteristic of the On-Line and Decentralized Path-Planning for Multiple Automata," Springer-Verlag, Distributed Autonomous Robotic System, H. Asama, T. Fukuda, T. Arai, I. Endo (Eds.), 111-122, 1994.
7) R.A. Brooks: "A Robust Layered Control System for a Mobile Robot," IEEE Journal of Robotics and Automation, **RA-2**-1, 14-23,

1986.
8) S. Ishikawa and S. Asaka: "A Method of Piloting an Autonomous Mobile Robot in Dynamically Changing Environment Including Moving Obstacles," Journal of the Robotics Society of Japan, **11**-6, 856-867, 1993.
9) S. Yuta and S. Premvuti: "Cooperating Autonomous and Centralized Decision Making to Achieve Cooperative Behaviors Between Multiple Mobile Robots," Proc. Int. Symp. on Disributed Autonomous Robotic Systems, 173-181, 1992.
10) S. Kato, S. Nishiyama and J. Takeno: "Cooperative Behavior of Multiple Mobile Robots by Applying Traffic Rules ," Journal of the Robotics Society of Japan, **12**-2, 291-298, 1994.
11) Y. Ishida, S. Tomita, H. Asama, K. Ozaki, A. Matsumoto and I. Endo: "Development of an Integrated Communication System for Multiple Robotic Agents," Proc. Int. Symp. on Distributed Autonomous Robotic Systems, 193-198, 1992.
12) H. Itakura, A. Matsumoto, H. Ishizuka, H. Asama, I. Endo, and Y. Ishida: "Research and Development of Autonomous and Decentralized Robotic System ACTRESS (No. 6) - Control of Mobile Robot Based on Sensor Information -," Lecture Papers on Precision Industry Association, Spring-Meeting in 1991, 965-966, 1991.

Name:
Koichi Ozaki

Affiliation:
Research associate, Department of Mechanical System Engineering, Faculty of Engineering, Utsunomiya University

Address:
Ishii 2753, Utsunomiya-shi, Tochigi, 321, Japan

Brief Biographical History:
1990-1992 - Graduate school (Master course), Toyo University
1992-1995 - Graduate school (Doctor course), Saitama University
1995-1996 - Postdoctoral researcher, RIKEN (The Inst. of Physical and Chemical Research)
1996 - Research Associate, Utsunomiya University

Main Works:
- "Development of Task Assignment System Using Communication," Journal of Robotics and Mechatronics 4-2, 122-127, 1992.
- "Synchronized Motion by Multiple Mobile Robots Using Communication," Proceedings of 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems, 1164-1169, 1993.
- "Negotiation Method for Collaborating Team Organization among Multiple Robots," Distributed Autonomous Robotic Systems, Springer-Verlag, 199-210, 1994.

Membership in Learned Societies:
- The Robotics Society of Japan (RSJ)
- The Japan Society of Mechanical Engineers (JSME)
- The Japan Society of Precision Engineering (JSPE)

Name:
Yoshiki Ishida

Affiliation:
Lecture, Kyushu University, KITE Network Operation Center, c/o Computer Center, Kyushu University

Address:
Hakozaki 6-10-1, Higashiku, Fukuoka, 812-12 Japan

Brief Biographical History:
1986-1988 - Graduate school (Master course), the University of Tokyo
1988-1994 - Research associate, The University of Tokyo
1994 - Lecture, Kyushu University

Main Works:
- "Development of Task Assignment System Using Communication," Journal of Robotics and Mechatronics, 4-2, 122-127, 1992.
- "Synchronized Motion by Multiple Mobile Robots Using Communication," Proceedings of 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems, 1164-1169, 1993.
- "Negotiation Method for Collaborating Team Organization among Multiple Robots," Distributed Autonomous Robotic Systems, Springer-Verlag, 199-210, 1994.

Membership in Learned Societies:
- Internet Society Member
- The Institute of Electrical and Electronics Engineers (IEEE)
- The Robotics Society of Japan (RSJ)

Name:
Akihiro Matsumoto

Affiliation:
Associate professor, Department of Mechanical Engineering, Faculty of Engineering, Toyo University

Address:
2100 Kujirai, Kawagoe, Saitama, 350, Japan

Brief Biographical History:

1981-1983 - Graduate school (Master course), The University of Tokyo
1983-1988 - Research associate, The University of Tokyo
1988-1990 - Assistant professor, Toyo University
1990 - Associate professor, Toyo University
1994-1995 - Visiting researcher at the University of Lous Pasteur Strasbourg (France)

Main Works:

- "The Industrial Robot Language 'SLIM'," Japan Standards Association, Tokyo, 1994. (in Japanese)
- "Development of Task Assignment System Using Communication," Journal of Robotics and Mechatronics 4-2, 122-127, 1992.
- "Synchronized Motion by Multiple Mobile Robots Using Communication," Proceedings of 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems, 1164-1169, 1993.
- "Negotiation Method for Collaborating Team Organization among Multiple Robots," Distributed Autonomous Robotic Systems, Springer-Verlag, 199-210, 1994.

Membership in Learned Societies:

- The Robotics Society of Japan (RSJ)
- The Japan Society of Precision Engineering (JSPE)
- The Japan Society of Mechanical Engineers (JSME)
- The Institute of Electric and Electronic Engineers (IEEE)
- Japan Robot Association (JARA)

Name:
Isao Endo (see p.426)

Name:
Hajime Asama (see p.426)