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Mobile Robot with Eyeball Expression as the Preliminary-Announcement and Display of the Robot's Following Motion

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Abstract. This paper explains the PMR-2R (prototype mobile robot –2 revised), the mobile robot with the eyeball expression as the preliminary-announcement and display of the robot's following motion. Firstly, we indicate the importance of the preliminary-announcement and display function of the mobile robot's following motion for the informational affinity between human being and a robot, with explaining the conventional methods and the related works. We show the proposed four methods which are categorized into two types: one type which indicates a state just after the moment and the other type which displays from the present to some future time continuously. Then we introduce the PMR-2R, which has the omni-directional display, the magicball, on which the eyeball expresses the robot's following direction of motion and the speed of motion at the same time. From the evaluation experiment, we confirmed the efficiency of the eyeball expression to transfer the information. We also obtained the announcement at around one or two second before the actual motion may be appropriate. And finally we compare the four types of eyeball expression: the one-eyeball type, the two-eyeball type, the will-o'-the-wisp type, and the armor-helmet type. From the evaluation experiment, we have declared the importance to make the robot's front more intelligible especially to announce the robot's direction of motion.

Keywords: human-friendly, mobile robot, informational affinity, action and intention, preliminary-announcement and display, eyeball expression, Omni-directional display

1. Introduction

1.1. Background and Purpose

This study aims at establishing the preliminary-announcement and display method with a simple device by which a mobile robot's following action and intention can be intuitively transmitted to surrounding people.

Applying robotic technology to care and support human beings directly is expected, especially in Japanese society which has become an aging and decrease-in-the-birthrate society. The number of robot which lives and works sharing the same space with human being is increasing. And the distance between human being and robot is becoming shorter. Such robot has to avoid accident with human being. Robot is an artificial creatures, so it is difficult for human being to understand the robot's following action and intention.

Various safety functions to avoid accidents have been studied. These are the safeguard function that robot will stop if the robot approaches someone (Laschi et al., 2001; Prassler et al., 2001; Hans et al., 2002; Wandosell and Graf, 2002), the soft cover which is not painful to human being even if he/she contacts the robot (Iwata et al., 2000; Wichiert and Lawitzky, 2001), and the joint compliance control which makes the robot's joint soft directly (Morita and Sugano, 1997) or indirectly (Hashimoto et al., 2002).

Furthermore we focus on the informational affinity between human being and a robot. We think the preliminary-announcement and display function about the robot's following motion towards surrounding people before beginning to move is important on human-friendly robots.

1.2. Contents of this Paper

The rest of this paper is constructed as follows. Chapter 2 indicates the importance of the preliminary-announcement and display function of the robot's following motion for the informational affinity between a human being and a robot, with explaining the conventional methods and the related works. We show the proposed four methods which are categorized into two types: one type which indicates a state just after the moment and the other type which displays from the present to some future time continuously. Chapter 3 introduces the PMR-2R (prototype mobile robot –2 revised), which has the omni-directional display, the magicball, on which the eyeball can express the robot's following direction of motion and the speed of motion. In Chapter 4 we compare the four types of eyeball expression, the one-eyeball type, the two-eyeball type, the will-o'-the-wisp type, and the armor-helmet type, to solve the front recognition problem.

2. Preliminary-Announcement and Display of Mobile Robot's Following Motion

2.1. Conventional Method

2.1.1. Mobile Machine/System. Conventional mobile machine/system only tells its approaching. The transferred information is too simple and insufficient on affinity between human being and the machine. And in any conventional mobile machine/system, surrounding people are expected to keep away from the path of the machine. The automatic vehicle and the conveyance robot, such as in a factory and a hospital, light, blink or rotate a warning lamp, and/or they play a melody through a speaker. On automobiles, the driver's action and intention are indicated with the blinker, the back lamp, the brake lamp, and so on. These equipments are familiar example of the preliminary-announcement and display device. However, these devices are insufficient for the human-friendly mobile robot which lives and works more closely to human being.

On the other hand when a train approaches a station, the lamp will be lighted up and/or some guidance voice will be said on the station platform. In this case, the device to transfer the information can be installed at the facilities on the ground, because a train always runs on the same rail/track. This way is not practical for the human-friendly mobile robot because it doesn't move only on the same predetermined path.

2.1.2. Among Human Beings. Human being has no special equipment for preliminary-announcement and display of his/her following action and intention. But a person can anticipate other's action and intention by using the non-verbal information like the body language. For example, a person who passes through in bustle expects the other's direction of motion and the speed of motion, considering the other's direction of looking, the direction of foot stepping forward, the posture of arms to swing, and the full-body postures. Then he/she can behave according to the recognition about others' action and intention. Such non-verbal information is based on the form and the property of human body and the customs in daily life. Human being shares the knowledge and information about the property and customs to each other as the common sense. But it is difficult for human being to understand the robot's action and intention from its outward appearance and the posture, because all robots may not have a human-like configuration and it must not act like a human being.

2.2. Related Works

Image analysis have been made in order to read the human action and the intention for a face or gaze interface to control some instructions (Matsumoto et al., 2001) or to communicate between human being and a machine (Mukawa et al., 2001). Moreover emotion analysis by processing an image has been made partially (Morishima et al., 2001; Nahas et al., 2001).

On the other hand from a robot to a human being, there have been a few researches. WAMOEBA, a mobile robot of Waseda University, can present its internal condition such about the buttery and the temperature on the display at its breast (Ogata and Sugano, 2000). About the description of the robot's following motion, there are two previous works especially on the manipulator. AIST (National Institute of Advanced Industrial Science and Technology) proposed the function to project some mark on an object which the robot is going to take in the sharing space between a human being and the robot (Wakita et al., 2001). Mie University reports the experiment of an industrial robot being equipped with multiple LEDs on its end-tip to indicate its motion aiming to support eating for handicapped people (Hagiwara et al., 2003). Human-like face to communicate have been studied so much (Breazeal, 2000; Fukuda et al., 2001; Hara et al., 2001; Kobayashi et al., 2001; Kozima and Vatikiotis-Bateson, 2001), but all robot must not be a humanoid robot (Yamaguchi and Takanishi, 1997; Hirai et al., 1998; Kagami et al., 1998; Inoue et al., 2001).

2.3. *Proposed Method*

Robot should have a certain method to announce and display its following action and intension while moving in a human-coexisting environment, since a person doesn't necessarily share the same common sense with robots. The robot's action and intention don't have to be transferred by the same way of human being, because a mobile robot doesn't always have the similar configuration with human being. Information should be transferred in the robot's own way. But it must be easy for human being to understand with the ordinary common sense. And it should be simple and intelligible way as much as possible to become acceptable for human being.

Here in our research we think about the impact avoidance between a person and a mobile robot (Fig. 1). If a person can understand whether the robot is going to stop or run straight faster, or whether the robot will step a side to avoid some obstacle, he/she can decide the reaction according to the robot's announcement. So we think two kinds of information, the direction of motion and the speed of motion, must be displayed on the mobile robot which moves on a two dimensional plane. The preliminary-announcement and display function of the robot's following motion is necessary not only on the autonomous type robot but also on the remote-operated type robot.

Figure 1. Impact avoidance.

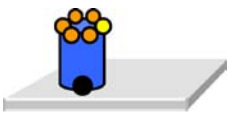
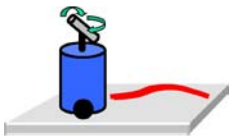
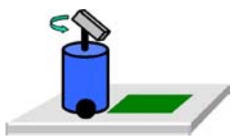
We have proposed four methods until now as shown in Table 1. These four methods are categorized into two types: one type whish indicates a state just after the moment and the other type which displays from the present to some future time continuously.

2.3.1. Indicating a State Just After the Moment.

(1) *Lamp*: Several lamps are arranged on the mobile robot's upper surface at a circumference. Only the direction of motion along which the robot is going to move is announced by turning on the lamp at that direction. The speed of motion at which the robot is going to move is also displayed by the blinking rate or the different colors of the lamp.

(2) *Party-blowouts*: Party-blowouts is a gadget. Blowing air into a cylinder extends blowouts, and stopping the blowing rewinds from the top. Blowouts is settled on a turntable which is put on the mobile robot's upper surface. The speed of motion is

Table 1. Proposed methods.

(1) Indicating a state just after the moment		(2) Displaying from present to some future time continuously	
(a) Lamp	(b) Party-blowout (elastic arrow)	(c) Beam-light	(d) Projector
			
Several lamps arranged on upper surface. Only direction of motion by turning on the lamp. Speed of motion also by blinking rate or different colors.	Party-blowouts settled on turn table. Speed of motion by length of blowouts. Direction of motion by tip direction of blowouts. Two kinds of information at the same time.	Beam-light draws scheduled path on the ground from present to some future time using pitch-yaw mechanism. Situation on the way is also displayed.	Projector projects two dimensional image on the ground. Not only scheduled path but also additional information can be seen on the image

announced with the length of blowouts. And the direction of motion is displayed with the tip direction of blowouts. By using blowouts, the two kinds of information, the speed of motion and the direction of motion, can be announced, for example, at 1.0 second before the actual motion at the same time. Party-blowouts mentioned here only means some linear object whose length or thickness needs to change like an elastic arrow and the direction of the object can be adjustable. It is not necessary to be the very party-blowouts made of paper, expanded and contracted by blowing air.

2.3.2. Displaying from Present to Some Future Time Continuously.

(1) *Beam-of-light*: The beam-of-light draws the scheduled path directly on the ground from the present to some future time, for example until 2.0 second later, with using a laser pointer and a two degree-of-freedom mechanism like pitch and yaw. The length of the drawn path shows the (average) speed of the mobile robot. Not only the state just after the moment but also the situation on the way can be displayed, such as a straight path or some curved path.
(2) *Projector*: Projector on the mobile robot's upper surface projects a two dimensional image on the ground. Not only the scheduled path but also some additional information like the robot's condition of a buttery, internal temperature, weakness of parts, and so on, can be displayed on the image. If the robot moves only forward like a two-wheel type and the projection area is wide enough, the projector can be fixed on the robot without an active mechanism like a turntable.

2.4. Previous Results on Simulation

Before making a hardware equipment to realize the idea, the software simulation system has been developed to examine the method and the timing suitable to announce and display the mobile robot's following motion. Mobile robot "chasing task" is adopted for the quantitative evaluation. The mobile robot moves about at a random speed in a random direction. Subject person operates the operation robot by using joystick trying to correspond the operation robot with the mobile robot, with looking at the preliminary-announcement and display on the mobile robot. The path of the mobile robot shows the actual motion of a robot. The path of the operation robot reflects the recognition of a human being. So the method and the timing to announce and display the following motion are evaluated numerically with the position gap and the direction gap between the mobile robot and the operation robot on trying to correspond.

We examined about four methods, the lamp without speed information, the lamp with changing its color as the speed information, the blowout, and the beam-of-light, and about six timings, every 0.5 second until 3.0 second before the actual motion. We have carried out the experiment on one degree-of-freedom motion, the translation and the rotation, separately at first. Then we checked on the two degree-of-freedom motion with the robots which move on a two dimensional plane.

As the result, the following conclusions have been confirmed.

- Preliminary-announcement not only the direction of motion but also the speed of motion is important for the announcement of mobility.
- The beam-of-light type, the method displaying from the present to some future time continuously, is easy to understand the robot's following motion. But some amount of length of the drawn path is necessary, which means an appropriate timing to announce, depending on the conditions like the speed of motion, the size of the mobile robot, and so on.
- Party-blowout is more effective than lighting lamp, on the method indicating a state just after the moment. It seems that human being tend to understand some information with a transforming object rather than with a color-changing object, and the continuous changing seems better than the distributed changing.
- The suitable timing to indicate a state is around 1.0 second before the actual motion. If the time difference is too much long, the position gap and the direction gap become long due to the poor human memory. To the contrary if the time difference is too much short, the operation will be rate owing to the human reaction delay.

3. Mobile Robot PMR-2R with Preliminary Announcement and Display Function of Following Action and Intention

After the simulation, we developed the PMR-2R. PMR-2R is a mobile robot with the omni-directional display, the magicball (R), on which the eyeball can express the robot's following speed of motion and the direction of motion (Fig. 2).

Figure 2. PMR-2R with eyeball expression.

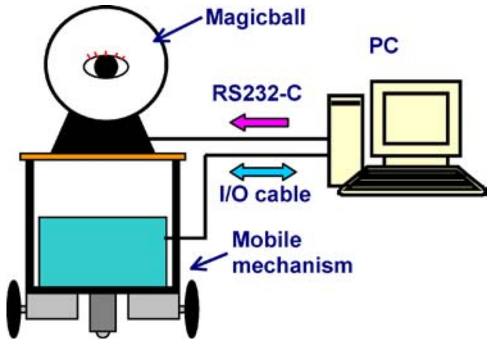


Figure 3. Communication with PC.

3.1. Eyeball Expression

3.1.1. Eyeball on Display. The eyeball is adopted as the picture to be displayed on the magicball. The eyeball expression can indicate the robot's state just after the moment. This is developed from the method with multiple lamps in Table 1.

We think the preliminary-announcement method should be intuitive so that even if someone watches it for the first time he/she can guess the meaning with the ordinary common sense. The direction of looking is a key when a human being predicts and understands the other's action. The robot will become friendlier for human being with the eyeball expression when considering the characteristic and preconception of human being.

3.1.2. Magicball. The magicball is made from Lumino Licht Elektronik GmbH. The ball has 0.3 [m] on diameter and 0.39 [m] on total height including the electric circuits. By ultra high-speed rotation of the 32 pieces $\times$ 3 lines of LED (light emitted diode), the characters and the pictures can be displayed on the side of the magicball in eight colors (white, yellow, azure, blue, green, red, and black) at 0.09 [m] on height. The characters and the pictures can be easily rotated, blinked, and become still on the display. If some message is made go around on the display the message can be seen from every direction of 360 degrees around the display. The characters and the pictures are simply inputted on a PC-Windows and stored in the memory in the magicball as an image frame. Each frame has 256 $\times$ 32 [dot]. The communication command through RS232-C from the PC calls an image frame from the memory on magicball, and the frame is displayed (Fig. 3). Due to the communication time delay through RS232-C and the required period to read and display the frame, we settled the image could be renewed in 0.5 second at least.

3.1.3. Speed of Motion and Direction of Motion. The eyeball expressions on the magicball corresponding to the mobile robot's motion are summarized in Table 2. The robot expresses the direction of motion along which it will move from now on with the directional position of the eyeball on the side of the magicball. The robot expresses the speed of motion at which it will move from now on with the thickness of the eyeball. So the eyeball can indicate these two kinds of information simultaneously. The target motion of the mobile robot is following four kinds: going straight (normal/slow speed), stop (stand still), turn (large/small, right/left), and spot revolution.

(1) *Speed of motion*: The thickness of the eyeball, which means the wideness between the upper eyelid and the lower eyelid, is changed according to the speed of motion of the mobile robot (Fig. 4). That is, the eye is closed when the robot stands still, the eye is opened thinly when moving slowly, and the fully opened eye means the moving at the normal speed.

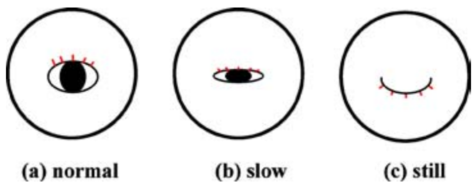
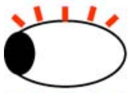
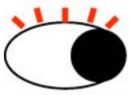
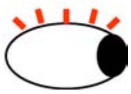


Figure 4. Speed of motion.

Table 2. Eyeball expression.

Robot's motion	Eyeball expression: Form	Eyeball expression: Position
Stop (stand still)		Front
Go straight (normal speed)		Front
Go straight (slow speed)		Front
Turn right ($r = 1.5$[m])		Right (at 30 [deg])
Turn right ($r = 0.5$[m])		Right (at 60 [deg])
Spot (right) revolution		Right (at 90 [deg])
Turn left ($r = 1.5$[m])		Left (at 30 [deg])
Turn left ($r = 0.5$[m])		Left (at 60 [deg])
Spot (left) revolution		Left (at 90 [deg])

That makes easy for surrounding people to find out the eyeball on the magicball rather than changing the total size of the eyeball. Even if the mobile robot moves slowly or stops, the width of the eyeball is kept as the same as that of the normal eye. And the operation to make the eye thin or wide in the up-and-down direction is like the manner of human being, so a person may have friendly feeling towards the robot.

(2) *Direction of motion*: Eyeball is displayed at 30 and 60 [deg] from the front on the side of the magicball for the small turn (0.5 [m] on radius) and the large turn (1.5 [m] on radius) respectively (Fig. 5). The spot revolution is considered as the special case of the turn with zero radius. So the eyeball is located just at the right or left for the spot revolution.

Moreover not only the directional position of the eyeball from the robot's front but also the position of

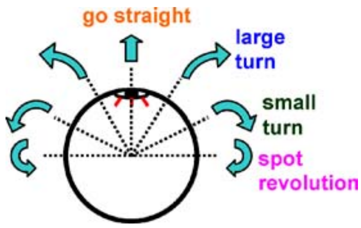


Figure 5. Direction of motion. (looking down from the above).

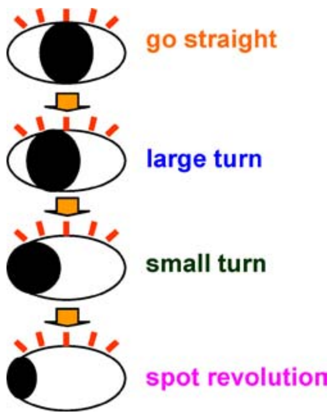


Figure 6. Iris position.

the iris on the eyeball is changed according to the radius of the turn (Fig. 6). When a person looks at something to move, not only he/she turn the head but also the iris is moved on the eye at the same time. Surrounding people can estimate the directional position of the eyeball on the magicball even if he/she can watch only the eyeball. The eyeball expression becomes more natural with the human-like manner.

3.1.4. Transition and Continuity. The transition and continuity make the eyeball expression more natural and usual. If the transition is not considered, for example, in the case that the mobile robot changes its motion from the right-large-turn (the eyeball is displayed at 30 [deg] from the front on the right) to the left-small-turn (the eyeball is positioned at 60 [deg] from the front on the left), the eyeball is erased and re-appeared at a large space immediately. Surrounding people feels it unnatural and tends to lose the eyeball with this operation. To make the surrounding people easy to follow the eyeball on the magicball, the transition of the eyeball should be considered when changing the eyeball expression (Fig. 7). Furthermore every 30 [deg] to display is a little wide to a natural feeling. So we decided the eyeball

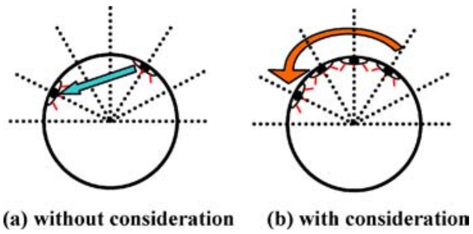


Figure 7. Transitivity.

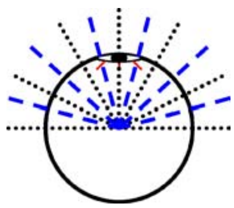


Figure 8. Continuity.

is displayed more frequently at every 15 [deg] for the continuity (Fig. 8).

3.2. *Mobile Mechanism*

PMR-2R has two driving wheels on both sides and two followers on the front and the back (Fig. 2). PMR-2R can go forward/backward and rotate on the spot, so it can move to all directions. The maximum speed on translation and on rotation is 0.22 [m/s] and 60 [deg/s] respectively. The payload is set to 50 [kg] including the robot's own weight. The "freebear (Freebear Corp.)" with the load-proof of 40 [kg] is adopted as the follower.

The driving wheels are driven by the DC servo motor with the optical encoder through the harmonic drive mechanism (Harmonic Drive Systems Inc.) and the miter gears (Kyouiku Gear MFG, Co. Ltd.). The robot's weight is supported with the wheel shafts and the bearings not to apply some thrust load on the motor shaft. The spiral miter gears are used to reduce the backrush. PC controls the DC motor through a DA board (Interface Corp.) and a speed control type driver (Okazakisangyo Co. Ltd.). The output pulse from the encoder is transmitted to the PC through a counter board and the data is used as the position (angle) information. Thus we can control both the mobile mechanism through the interface boards and the eyeball expression through RS232-C at the same time from one PC (Fig. 9). The PC is now separated from the PMR-2R, but it will be equipped on the robot before long.

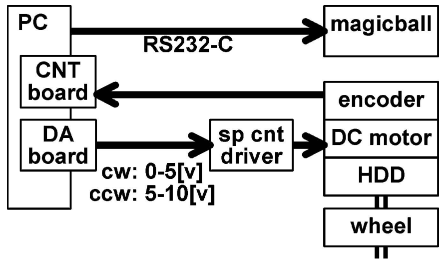


Figure 9. Control architecture.

4. Evaluation Experiments

In order to examine the visibility and the validity of the eyeball expression on PMR-2R as the announcement method, PMR-2R is exhibited for show at the "RT (robotic technology) Exchange Plaza", which was held on September 2002 in Tokyo. The event is to introduce and exchange the technology and the patents among the universities, the national laboratories, and the industries.

4.1. *Details of Demonstration*

We prepared three courses to demonstrate the PMR-2R. The robot moves along the course with announcing its following motion. Course-1 includes the large turn (1.5 [m] radius), the small turn (0.5 [m] radius), and the spot revolution (Fig. 10, and Table 3). The speed of motion is also changed along the straight line with the fully-opened eyeball, the half-closed eyeball, and the completely-closed eyeball. Course-2 is a little longer and more complicated than Course-1 (Fig. 11, and Table 4). Course-3 is intended to demonstrate at a smaller space, so it consists of only a straight line and the small turn (Fig. 12, and Table 5).

4.2. *Procedure to Evaluate*

The purpose and the background of this study are explained to the visitors at first. And the functions and features of the robot are told while the robot moves along the course giving the eyeball expression corresponding to the robot's motion just at that time. So the eyeball expression corresponding to the robot's motion can be understood by visitors. Then the previous results on the simulation are explained to visitors that the suitable timing for human being to be announced is around 1 [s] before the actual motion. So the robot is moved again along the course at the timing to announce of 1 [s] before and 2 [s] before the actual motion.

Table 3. Eyeball expression and robot's motion in Couse-1.

	Eyeball expression		
Point	Form	Position	Robot's motion
1		Front	Stop
1–2		Front	Go straight
2–3		Right (at 30 [deg])	Turn right ($r = 1.5$ [m])
3–4		Right (at 60 [deg])	Turn right ($r = 0.5$ [m])
4–5		Left (at 60 [deg])	Turn left ($r = 0.5$ [m])
5–6		Right (at 60 [deg])	Turn right ($r = 0.5$ [m])
6–7		Right (at 30 [deg])	Turn right ($r = 1.5$ [m])
7		Right (at 90 [deg])	Spot revolution (right)
7–8		Front	Go straight (normal)
			Go straight (slow)
8		Front	Stop
8–9		Front	Go straight (slow)
			Go straight (normal)
9		Front	Stop

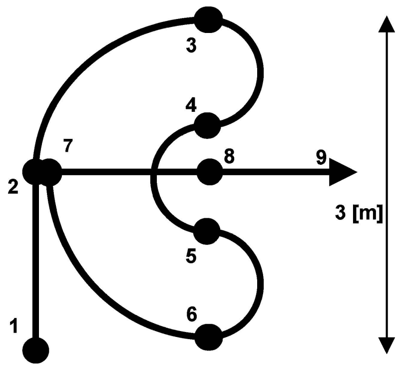


Figure 10. Course-1.

We asked the visitors to reply to the following three questions after the demonstration.

- The robot expresses the direction of motion along which it will move from now on with the directional position of the eyeball displayed on the side of the magicball. This method is positive/negative/other (can't judge)?
- The robot expresses the speed of motion at which it will move from now on with the thickness of the eyeball displayed on the magicball. This method is positive/negative/other (can't judge)?
- What do you think the most intelligible timing to be announced on the eyeball expression: just at that

Table 4. Eyeball expression and robot's motion in Course-2.

	Eyeball expression		
Point	Form	Position	Robot's motion
1		Front	Stop
1–2		Front	Go straight (normal)
			Go straight (slow)
			Go straight (normal)
2		Right (at 90 [deg])	Spot revolution (right)
2–3		Right (at 30 [deg])	Turn right ($r = 1.5$ [m])
3–4		Right (at 60 [deg])	Turn right ($r = 0.5$ [m])
4–5		Left (at 60 [deg])	Turn left ($r = 0.5$ [m])
5–6		Right (at 60 [deg])	Turn right ($r = 0.5$ [m])
6–7		Left (at 60 [deg])	Turn left ($r = 0.5$ [m])
7–8		Front	Go straight (normal)
			Go straight (slow)
8		Front	Stop

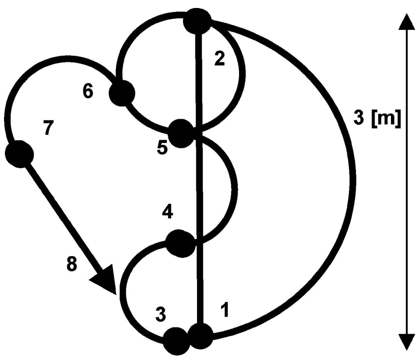


Figure 11. Course-2.

time (0 [s] before)/1 [s] before/2 [s] before the actual motion?

We prepared only three choices on each question to make it easy for visitors to answer. Some free comment is requested after the questions.

4.3. Result and Discussion

We obtained 35 replies (male: 31, female: 4). The replies to the question are collected as shown in Table 6. According to the questionnaire results, many people

Table 5. Eyeball expression and robot's motion in Course-3.

	Eyeball expression		
Point	Form	Position	Robot's motion
1		Front	Stop
1–2		Front	Go straight (normal)
			Go straight (slow)
2		Front	Stop
2–3		Front	Go straight (slow)
			Go straight (normal)
3		Right (at 90 [deg])	Spot revolution (right)
3–4		Right (at 60 [deg])	Turn right ($r = 0.5$ [m])
4–5		Left (at 60 [deg])	Turn left ($r = 0.5$ [m])
5–6		Right (at 60 [deg])	Turn right ($r = 0.5$ [m])
6		Right (at 90 [deg])	Spot revolution (right)
6		Front	Stop

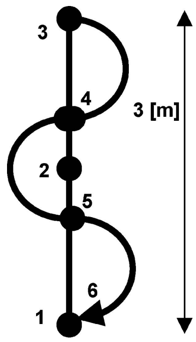


Figure 12. Course-3.

approved of the effectiveness of the eyeball expression as the announcement method especially on the direction of motion. More than four-fifth of the replied persons understand the robot's following direction of motion with the directional position of the eyeball on the magicball. None of them has negative impression to this way to express. About two-third of the replied persons are satisfied with the thickness of the eyeball to express the robot's following speed of motion. Only one-tenth persons don't agree with this way to express, and the negative person is all at the early middle age in 20s and 30s. About the timing to announce, almost half of the replied person answered that 1 [s] before the actual motion is the most intelligible, that is the same as the result on the simulation. However one-third persons answered that 2 [s] before is more intelligible. As people become older, more people like 2 [s] before the actual motion. Someone said that the medium timing between 1 and 2 [s] before the actual motion might be the best, as a comment. We think the timing to announce depends on various

Table 6. Questionnaire result on direction, speed, and timing.

Subject		Direction (%)			Speed (%)			Timing (%)		
Age	Num	good	–	bad	good	–	bad	0 [s]	1 [s]	2 [s]
20–29	12	75	25	0	67	33	0	0	67	16
−39	10	80	20	0	40	40	20	10	40	40
−49	5	100	0	0	60	20	20	0	40	40
−59	6	83	17	0	100	0	0	0	33	67
−69	2	100	0	0	100	0	0	0	50	0
Total	35	83	–	0	66	25	9	3	49	34

conditions, such as the maximum/average speed of the mobile robot, the size of the mobile robot, and so on. So we have to examine more on the timing to announce with considering the human physiological characteristics.

5. Four Types of Eyeball Expression

5.1. Problem: Front Recognition

We noticed through the above-mentioned experiment that the recognition of the robot's front is very important on the eyeball expression. The radius at the turn is expressed as the angle between the robot's front and the displayed eyeball on the magicball. But it is difficult to distinguish the front of the robot, because the magicball has a globular form as the omni-directional display. So we should make the robot's front easy for a person to distinguish.

5.2. Details of the Four Types of Eyeball Expression

We worked out the following four types of the eyeball expression including the previous one to solve the front recognition problem: the one-eyeball type, the two-eyeball type, the will-o'-the-wisp type, and the armor-helmet type (Fig. 13). Front view of the robot with the four types of the eyeball expression when the directional position of the eyeball on the magicball is changed is shown in Table 7.

(1) *One-eyeball type*: This type is the same as the previous expression.
(2) *Two-eyeball type*: The two-eyeball type makes the magicball like a human face, so the robot will become more friendly and familiar to human being. The displayed image is widely spread on the magicball, so surrounding people become easy to recognize the change of the eyeball expression. This will support for a person to distinguish the small turn, the large turn, and the spot revolution. When the speed of motion of the mobile robot is changed, the thickness of the eyeball is adjusted as on the one-eyeball type, as shown in Fig. 14(b).
(3) *Will-o'-the-wisp type*: The will-o'-the-wise type is aimed at making the robot's front intelligible for surrounding people on purpose. The eyeball leaves the tail from the fixing point in the front like an elastic band when changing its directional position on the magicball. When the speed of motion of

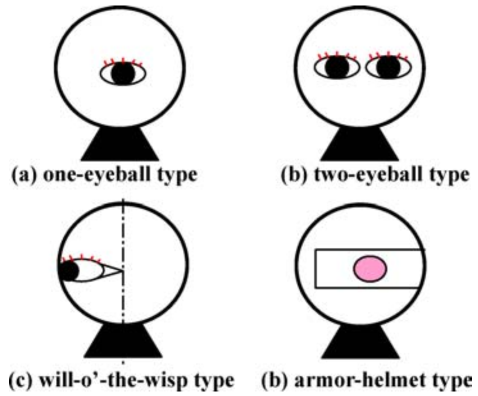


Figure 13. Four types of eyeball expression.

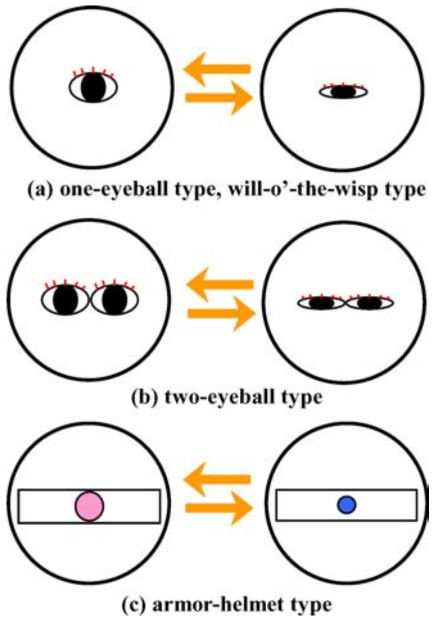
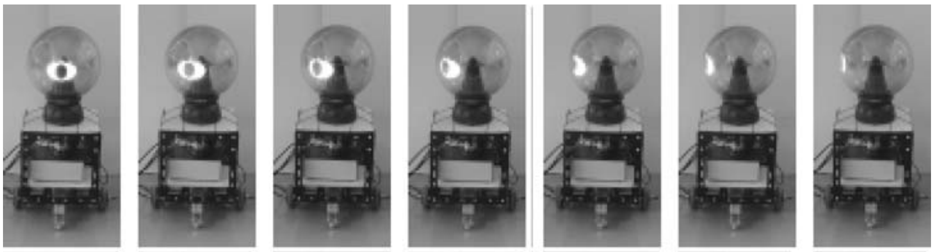
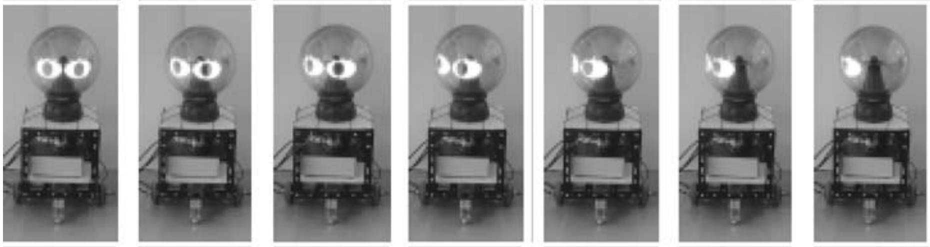
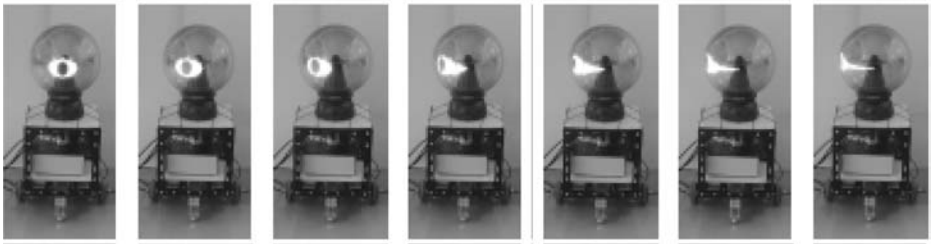
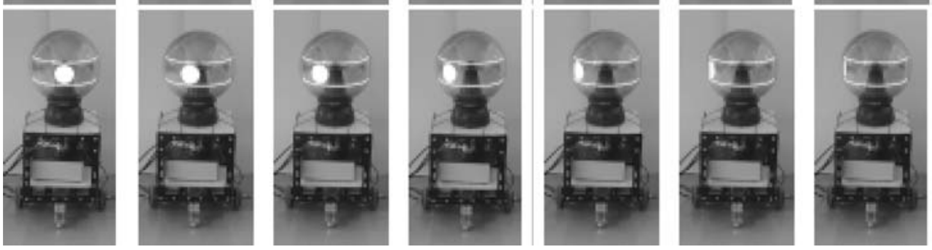


Figure 14. Speed of motion on four types of eyeball expression.

Table 7. Four types of eyeball expressions when changing the directional position on magicball.

Types	at 00 [deg]	at 15 [deg]	at 30 [deg]	at 45 [deg]	at 60 [deg]	at 75 [deg]	at 90 [deg]
One-eyeball type							
Two-eyeball type							
Will-o'-the-wisp type							
Armor-helmet type							
	go straight		large turn		small turn		spot revol.

the mobile robot is changed, the thickness of the eyeball is adjusted as on the one-eyeball type, as shown in Fig. 14(a).

(4) *Armor-helmet type*: The armor-helmet type has a fixed frame in the range of 180 [deg] at the front. The circular eyeball moves to right or left only inside the frame. The fixed frame is useful to find the robot's front. To announce the speed of motion, the color of eyeball is changed with its size, as shown in Fig. 14(c); the large pink eyeball is for the normal speed and the small blue eyeball is for the slow speed. The eyeball is erased and only the frame is remained for the stop motion.

5.3. *Evaluation Experiment*

The evaluation experiment was carried out to compare the intelligibility of the four types of the eyeball expression.

5.3.1. Procedure to Evaluate. The subject persons are seven male students in early twenties. After explaining the background, the purpose of this study, and the feature of PMR-2R to them, we demonstrated the robot's motion with the eyeball expression along the Course-3. The eyeball is displayed at the timing of 1 [s] before the actual motion on each eyeball expression.

After showing the four types of the eyeball expression along the same course, we obtained replies to the following questions about the direction of motion and the speed of motion at the maximum score of five points.

- How about the expression for the direction of motion? - very good/good/average/poor/very poor
- How about the expression for the speed of motion? - very good/good/average/poor/very poor

Free comment is requested after the questions.

5.3.2. Result and Discussion. The replies to the questions are summarized as shown in Table 8. The two-eyeball type and the will-o'-the-wisp type have relatively high score both on the direction of motion and the speed of motion. But the armor-helmet type has the highest score about the direction of motion. Anyway the importance to make the robot's front more intelligible is quite obvious especially for the announcement of the robot's direction of motion.

An opinion on the direction of motion is like the following; "It is difficult to distinguish the spot revolution from the right/left turn." We don't think it is a mistake that the spot revolution is considered as a special case of the turn with the zero radius. It may be better if the eyeball is displayed backward on the magicball further than just right or just left for the spot revolution. But how much the eyeball should be withdrawn may be decided considering many factors like the speed and the size of the robot.

The comment on the speed of motion is as follows; "The color of the eyeball should be changed with the thickness (wideness/size)", "The small eyeball on the slow speed is difficult to be aware of even with changing its color on the armor-helmet type".

Table 8. Questionnaire result on direction of motion and speed of motion.

Eyeball expression		One-eyeball	Two-eyeball	Will-o'-the-wisp	Armor-helmet
Direction of motion	good	-	1	1	**3**
	|	2	**4**	**3**	**3**
	|	1	1	2	-
	|	**4**	1	1	1
	bad	-	-	-	-
Speed of motion	good	2	3	2	1
	|	**4**	**4**	**4**	1
	|	1	-	1	2
	|	-	-	-	**3**
	bad	-	-	-	-

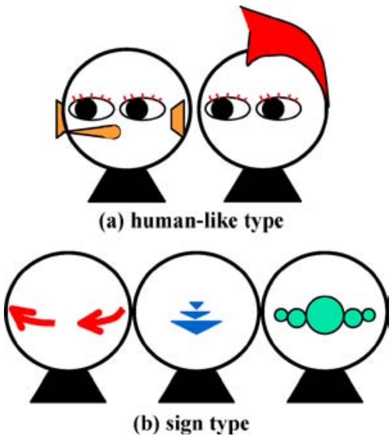


Figure 15. Other expressions on magicball.

We should design some better expression which is easy for a person to understand. The magicball has a globular from, so it might be better we will attach some ear-like object on both sides or we will put something like hat or cockscomb on the magicball (Fig. 15).

We now find more difficulty on the timing to display. It takes long time to display from some expression for a motion to the other expression for the next motion. Because we are considering both the transition and the continuity, so we have to display many eyeball expressions during the two motions. But it takes 0.5 [s] to refresh the displayed eyeball due to the communication time delay through RS232-C and the required period to read and project the image frame. In some cases, the motion has been done before the eyeball expression for the motion is displayed. For example, the robot would stop before the closed-eyeball for the stop motion appears on the magicball. The transition and the continuity make the eyeball expression intelligible and they raise the affinity for human being. But if we put the priority on the transition and the continuity, the eyeball expression can't match the robot's motion correctly. We should also think some appropriate omission on eyeball expression between the motions with considering the speed of changing the robot's motion.

6. Conclusion

This paper explained the PMR-2R, the mobile robot with the eyeball expression as the preliminary-announcement and display of the robot's following motion.

- Firstly, we have indicated the importance of the preliminary-announcement and display function of the mobile robot's following motion for the informational affinity between human being and a robot, with explaining the conventional methods and the related works. We have shown the proposed four methods which are categorized into two types: one type which indicates a state just after the moment and the other type which displays from the present to some future time continuously.
- Then we introduced the PMR-2R, which has the omni-directional display, the magicball, on which the eyeball expresses the robot's following direction of motion and the speed of motion at the same time. From the evaluation experiment, we have confirmed the efficiency of the eyeball expression to transfer the information. We also obtained the announcement at around one or two second before the actual motion may be appropriate.
- And finally we have compared the four types of eyeball expression: the one-eyeball type, the two-eyeball type, the will-o'-the-wisp type, and the armor-helmet type. From the evaluation experiment, we have declared the importance to make the robot's front more intelligible especially to announce the robot's direction of motion.

Future work includes more examination on the timing to announce regarding the response time of the magicball and considering the characteristic and preconception of human being. The eyeball expression has evaluated after we explained the meaning of each expression to the subject person in the above-mentioned experiment. The eyeball expression should also be evaluated by the subject person who looked at the robot for the first time. We don't mind so much for the first encounter situation between a person and the robot. Because a person usually watch the other's behavior for a while when a person meet the other person for the first time, then he/she decides the attitude to the other and the space between them. If a person looks at PMR-2R for a while, he/she may understand the relationship between the eyeball expression and its behavior. Certainly the first impression from the outward appearance and some manner is very important for the human-friendly robot.

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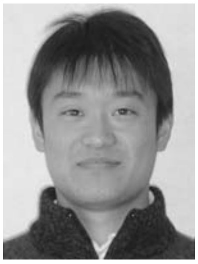

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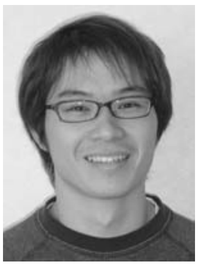

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