Expression of Intention by Rotational Head Movements for Teleoperated Mobile Robot

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***Abstract*—We are studying a teleoperated mobile robot that provides useful information to a pedestrian. However, it is difficult for people to understand meanings of actions, motions or movements of many conventional robots. The purpose of this study is to improve pedestrian's impressions of a robot. Especially this paper describes people's understandability of robot behaviors when a robot turns around a corner or when a person and a robot pass each other in a corridor. Our robot shows its intention to make turn by rotating its head, as though a pedestrian shows a traveling direction by his/her gaze or face direction. The robot is teleoperated by an operator for safety in public spaces, and the direction of the robot head and the moving direction of the robot body are determined by an artificial potential field (APF) generated by a target position given by the operator, positions of obstacles and pedestrians. The APF for a pedestrian is generated based on her/his personal space of a person. Thus, the robot can express the intention of its action by rotating the head to look where it is going, when the robot changes its direction around pedestrians. The intention expression can be natural and understandable for them by the rotational movement of the head before the robot turns its body actually. Impression evaluation experiments with questionnaires were conducted under the two kinds of situations to reveal the validity and effectiveness of the intention expression by the robot's head rotation. Significant differences related to understandability and some impression words were observed between with and without rotating the head.**

I. Introduction

In recent years, many robots used in public spaces are studied and developed as social robots actively. The personal home robots, such as the robot vacuum cleaner, Roomba (iRobot Corp.) [1], the therapeutic robot, PARO (AIST) [2] and so on, gradually gained social acceptance. Moreover, several services or conversational robots [3] [4] [5] are studied to evaluate their validity in public places, such as a shopping mall or cafeteria where there are many people.

However, when a service robot wanders among pedestrians actively in a public space, there are several problems to be solved. One of the problems is that it is difficult for people to understand intention of actions of a robot by its appearance, for example, which direction the robot is going to go, or what it is going to do. Moreover, the robot without a human-like appearance makes a negative influence on people's understandability. These confusing problems might make people threatened [6]. Several approaches have been proposed for preventing this problem. Kanda et al. have proposed a guide robot for a shopping mall, that shows more friendly attitude depending on how many times a customer has visited the mall [7]. Carton et al. have proposed a trajectory planning method that improves a human-like approach action of a mobile robot [8]. Andrist et al. [9] and Admoni et al. [10] have discussed the importance of robot's gaze in human-robot interaction. In order the robot to provide a better impression on surrounding people, it is necessary to improve the understandability of its behaviors.

One of the solutions is that a robot expresses an intention of its action or motion more clearly to people. Autonomous cars use direction turn signals, brake lights or reversing lamps in the same way as normal cars [11] [12]. Barak et al. have proposed the light interface for expressing the internal states of the robot to people depending on the situations [13]. Ikeura et al. have proposed a previous notice method for a manipulator using LEDs [6]. The LEDs mounted on the end effector show its moving velocity, pass and end points before the manipulator moves. Shindev et al. have proposed an intention expression method for a manipulator or mobile robot using an arrow displayed by a laser projector [14]. The projected arrow shows the direction of robot's movement. Matsumaru has proposed a preliminary-announcement method for people around the mobile robot [15], four kinds of displaying methods using an omni-directional display, flat-panel display, laser pointer and projector were evaluated under four different conditions with or without displaying and vocalizing.

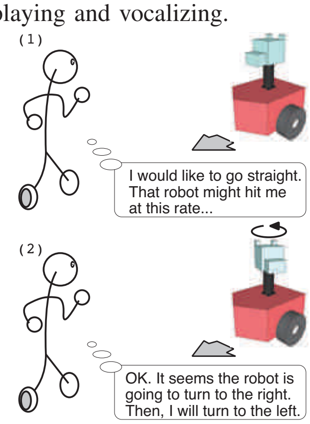

Fig. 1. Mobile robot with rotational head

This paper presents an intention expression method in a more natural way. When our mobile robot changes its traveling

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direction, the robot rotates its head to the direction where it will go, as though a pedestrian shows a traveling direction by her/his gaze or face direction. The mobile robot is teleoperated by a human operator for safety, because we are planning to apply this proposed method to a service robot in a local shopping street. However, he/she does not have to control all the robot actions but set a target position and moving speed and direction for the robot. The direction of the robot head is determined by an artificial potential field (APF) generated by a goal position specified by an operator and positions of both pedestrians and obstacles around the robot. Moreover, the APF for a pedestrian are generated based on a personal space of a person, and the personal space has two states: one is a walking state, the other is a stopped state. The robot head is rotated based on the calculated control input before the body is turned. As a result, surrounding people can know the robot's intention of trying to change a traveling direction in advance.

Two kinds of experiments are conducted to evaluate our proposed intention expression method using the robot head. One is when the robot turns around a corner, and the other is when a participant and the robot pass each other in a corridor. Experimental results reveal the validity and effectiveness of the proposed method.

II. Teleoperated Mobile Robot

A. System Configuration

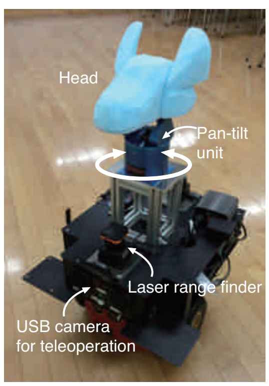


Fig. 2. Mobile robot with rotational head

Fig. 2 shows a mobile robot used in this paper. The mobile wheeled robot with a differential drive, Pioneer 3-DX (OMRON Adept Technologies, LLC.), is equipped with a laser range finder (LRF), UTM-30LX (HOKUYO Automatic Co., Ltd), and a pan-tilt unit, Biclops PT-M (TRACLabs, Inc.), for rotating a head of the robot. The head was designed as a shape of a dog's head as shown in Fig. 2. Although this head does not have any eyes, it is easy for surrounding people to understand the direction of the robot's head and body. The head is put on the pan-tilt unit, but only horizontal rotation function is used. An usb camera mounted on the robot is used for teleoperation.

A system configuration is shown in Fig. 3. A human operator teleoperates the mobile robot using a gamepad while watching a remote site video captured by the usb camera mounted on the robot.

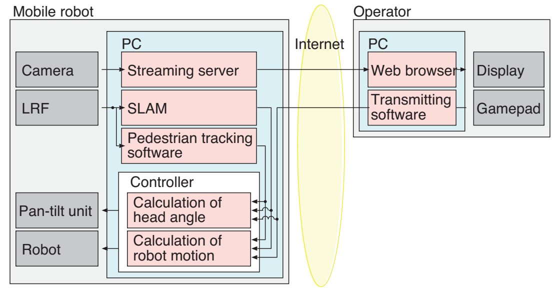


Fig. 3. Configuration of mobile robot teleoperation system

B. SLAM

The position ${}^{w}\boldsymbol{p}_r$ and orientation ${}^{w}\boldsymbol{R}_r$ of the mobile robot in the world coordinate system Σ_w can be estimated by a Simultaneous Localization And Mapping (SLAM) algorithm. Mobile Robot Programming Toolkit (MRPT) [16] is used for these estimations.

C. Pedestrian tracking

A particle-filter with a velocity-based motion model is used for detecting and tracking pedestrians [17] as shown in Fig. 4. The position ${}^{r}\boldsymbol{p}_p$, orientation ${}^{r}\boldsymbol{R}_p$ and velocity of a pedestrian in the robot coordinate system Σ_r can be estimated. This software can track multiple pedestrians at the same time. When multiple pedestrians pass each other, occlusions are happened in most cases. However, they can be tracked continuously.

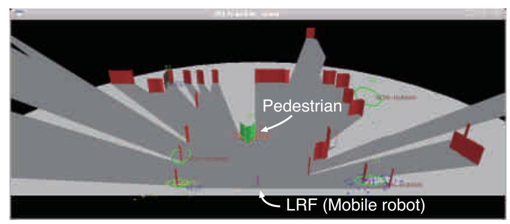


Fig. 4. Pedestrian tracking using LRF

III. Intention Expression

The direction of the robot head and the moving direction and velocity of the robot body are determined by APF generated by a control input for teleoperation and positions of pedestrians and obstacles around the robot. This section describes this control method

A. Personal space for pedestrian

The following four distance zones between two persons has been proposed by Hall [18]. (1) Intimate distance ($\sim$ 0.5 [m]), (2) Personal distance (0.5 $\sim$ 1.2 [m]), (3) Social distance (1.2 $\sim$ 3.6 [m]) and (4) Public distance (3.6 $\sim$). (1) is used for physical contact, (2) is for interactions with family and friends, (3) is the distance with business partners and (4) is outside the circle of involvement. And the shape of the personal space is a sphere or bubble. So the distance between a person and the robot should be more than the personal distance, let the shape the personal space for a standing person be the circle of the radius 1.2 [m] for simplification as shown in Fig. 5.

Yoda et al. have investigated several quantitative relations of parameters using subjective evaluation scales when a person and a mobile robot pass each other [19]. According to this paper, the following findings have been confirmed: (1) the appropriate lateral space between is more than 0.75 [m], (2) the appropriate distance where the robot starts avoiding a person is more than 2.38 [m] and less than 5.0 [m]. So, we designed the personal space for a walking person as shown in Fig. 5. The shape is an ellipse, and the major axis is in the moving direction. The distance between the centers of the person and the ellipse edge along the major axis is 2.38 [m], and the distance between the center of the person and the intersection of the ellipse with the left or right direction of the person is 0.75 [m]. The offset value between the center of the person and ellipse is d_o.

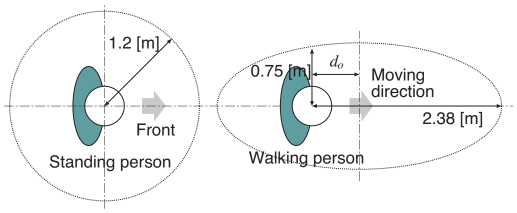


Fig. 5. Personal spaces of standing and walking persons

B. Intention expression using rotational head

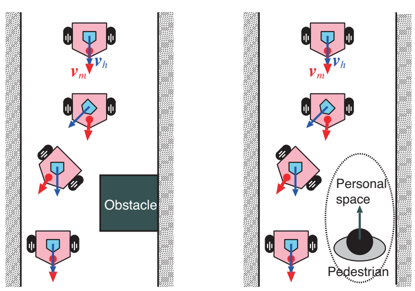


Fig. 6. Series of actions of robot head and body when robot pass obstacle or when pedestrian and robot pass each other

Fig. 6 shows typical series of actions of the robot head and body. When the robot is about to pass an obstacle or pedestrian, its head has been rotated before the body changes its moving direction.

C. Control based on APF

The task of the mobile robot is to reach a goal while avoiding pedestrians and obstacles. When the robot encounters pedestrians or obstacles, it turns its head as the intention expression to let them to know which direction it is going to go. APF proposed by Kim et al. [20] is basically used as a controller, we modify it for realizing the intention expression using the rotational robot head.

Fig. 7 shows the relations among a mobile robot, a goal, obstacles, pedestrians, and each coordinate system. The position ${}^w\boldsymbol{p}_r$ and orientation ${}^w\boldsymbol{R}_r$ of the robot in the world coordinate system Σ_w are estimated by a SLAM technique described in subsection II-B. The goal position ${}^w\boldsymbol{p}_g$ in Σ_w is set by an operator. The position ${}^w\boldsymbol{p}_{o_i}$ of an obstacle i $(i = 1 \sim \mathcal{N}_o)$ in Σ_w is also estimated by SLAM. The position ${}^w\boldsymbol{p}_{p_i}$ and orientation ${}^w\boldsymbol{R}_{p_j}$ of a pedestrian j $(j = 1 \sim \mathcal{N}_p)$ in Σ_w are estimated by the pedestrian tracker described in subsection II-C.

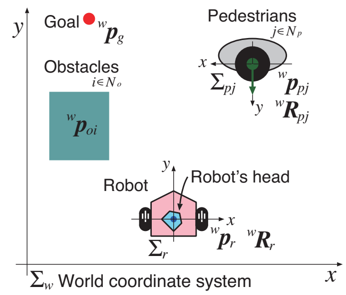


Fig. 7. Relations among robot, pedestrians and obstacles

The relative position between the robot position ${}^w\boldsymbol{p}_r$ and the goal position ${}^w\boldsymbol{p}_g$ in Σ_w is calculated by the following equation.

$$ {}^g\boldsymbol{p}_r = {}^w\boldsymbol{p}_r - {}^w\boldsymbol{p}_g \tag{1} $$

The potential field ${}^gU_r$ for that the robot reaches the goal is defined by:

$$ {}^gU_r = c_g \left(1 - \exp\left(-\frac{||{}^g\boldsymbol{p}_r||^2}{{l_g}^2}\right)\right) \tag{2} $$

where c_g and l_g are the constant values. c_g is the weight of the attractive force related to the goal, and l_g is the parameter related the range under the influence of the attractive force.

The relative position between the robot position ${}^w\boldsymbol{p}_r$ and the position ${}^w\boldsymbol{p}_{o_i}$ of the obstacle i in Σ_w is calculated by the following equation.

$$ {}^{o_i}\boldsymbol{p}_r = {}^w\boldsymbol{p}_r - {}^w\boldsymbol{p}_{o_i} \tag{3} $$

The potential field ${}^oU_r$ for that the robot avoids multiple objects is defined by:

$$ {}^oU_r = \sum_{i \in \mathcal{N}_o} c_o \exp\left(-\frac{||{}^{o_i}\boldsymbol{p}_r||^2}{{l_o}^2}\right) \tag{4} $$

where c_o and l_o are the constant values. c_o is the weight of the repulsive force related to an object, and l_o is the parameter related the range under the influence of the repulsive force.

Since the position ${}^r\boldsymbol{p}_{p_j} = ({}^rx_{p_j} \; {}^rx_{p_j})^T$ and rotation ${}^r\boldsymbol{R}_{p_j} = \begin{pmatrix} \cos{}^r\theta_{p_j} & -\sin{}^r\theta_{p_j} \\ \sin{}^r\theta_{p_j} & \cos{}^r\theta_{p_j} \end{pmatrix}$ of the pedestrian p_j in Σ_r, the relative position between the robot r and the pedestrian p_j is calculated by the following equation.

$$ \begin{aligned} {}^{p_j}\boldsymbol{p}_r &= \begin{pmatrix} {}^{p_j}x_r \\ {}^{p_j}y_r \end{pmatrix} \\ &= -\begin{pmatrix} \cos{}^r\theta_{p_j} & \sin{}^r\theta_{p_j} \\ -\sin{}^y\theta_{p_j} & \cos{}^r\theta_{p_j} \end{pmatrix} \begin{pmatrix} {}^rx_{p_j} \\ {}^ry_{p_j} \end{pmatrix} \end{aligned} \tag{5} $$

So we designed the potential field ${}^{p_j}U_r$ for that the robot avoids the pedestrian j by the following equation.

$$ {}^{p_j}U_r = c_p \exp\left(-\frac{w_{p_x}^2 ({}^{p_j}x_r - d_o)^2 + w_{p_y}^2 ({}^{p_j}y_r)^2}{l_p^2} \right) \quad (6) $$

where c_p and l_p are the constant values. c_p is the weight of the repulsive force related to a pedestrian, and l_p is the parameter related the range under the influence of the repulsive force. w_{p_x} and w_{p_y} are the weight coefficients in x and y directions respectively. Since there are $\mathcal{N}_p$ pedestrians, the total potential field of the pedestrians is calculated by the following equation.

$$ {}^{p}U_r = \sum_{j \in \mathcal{N}_p} {}^{p_j}U_r c_p \quad (7) $$

As described above, all the potential fields of the goal, obstacles and pedestrians have been defined. Then the total potential field is defined by the following equation using Eqs. (2)(4)(7) and the basic idea of the APF proposed by [20].

$$ {}^{r}U = \frac{1}{c_g} {}^{r}U_o {}^{r}U_g + {}^{r}U_g + {}^{r}U_p \quad (8) $$

Its corresponding force is defined by the following equation.

$$ {}^{r}\boldsymbol{f} = -\nabla {}^{r}U \quad (9) $$

Next, the force vector ${}^{h}\boldsymbol{f}$ for deciding the robot head direction is calculated based on Eq. (9) in the same manner.

D. Obstacle and pedestrian avoidance control

Since the non-holonomic mobile robot is used in this paper as shown in Fig. 2, the robot is controlled at the control point shown in Fig. 8. The robot can automatically reach a goal by Eq. (9) while avoiding obstacles and pedestrians as described in the previous subsection. On the other hand, the mobile robot is teleoperated by a human operator for safety as described in Section I. The operator inputs the moving direction and velocity for the robot by a controller, such as a stick of a gamepad, and let the operator's input be $\boldsymbol{v}_c$.

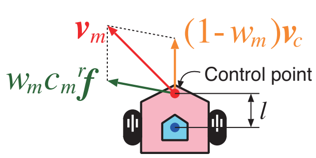


Fig. 8. Robot body controlled by APF and operator's inputs

As shown by Fig. 8, the directional vector $\boldsymbol{v}_m$ for controlling the mobile robot body is defined by:

$$ \boldsymbol{v}_m = w_m c_m {}^{r}\boldsymbol{f} + (1 - w_m)\boldsymbol{v}_c \quad (10) $$

where $w_m (0 \leq w_m \leq 1)$ is the weight coefficient, c_m is the coefficient for adjusting difference between the units of ${}^{r}\boldsymbol{f}$ and $\boldsymbol{v}_c$.

E. Head direction control

Although the head direction and the direction and velocity of the robot body are calculated based on Eq. (9), the head should be rotated earlier than the body movement. So the head angle is calculated at the virtual head position shown in Fig. 9. The virtual head position is located in front of the real head position. ${}^{r}f_y$ is the y component of ${}^{r}\boldsymbol{f}$, and c_v is the coefficient for adjusting the distance between the virtual and real head positions. The direction vector $\boldsymbol{v}_h$ of the robot head is defined by:

$$ \boldsymbol{v}_h = w_h \boldsymbol{v}_{f_h} + (1 - w_h)\boldsymbol{v}_c' \quad (11) $$

where $w_h (0 \leq w_h \leq 1)$ is the weight coefficient, c_h is the coefficient for adjusting difference between ${}^{r}\boldsymbol{f}$ and $\boldsymbol{v}_c$.

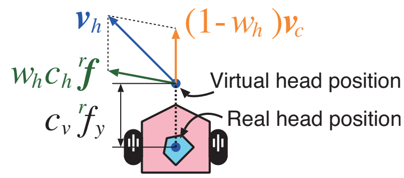


Fig. 9. Head direction decided by APF and operator's inputs

When the mobile robot is stopped, the robot turns its head to the nearest person with in 1.2 [m] based on the personal distance.

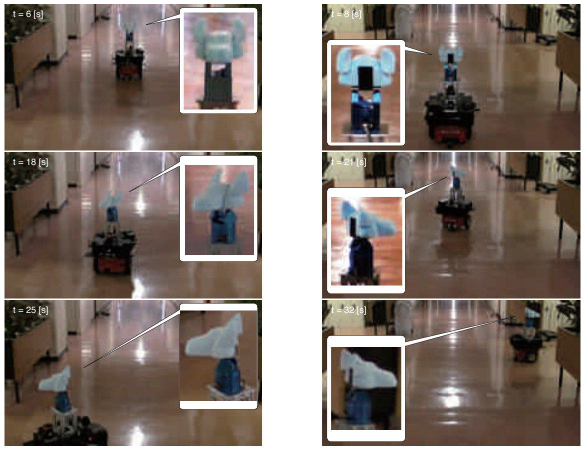
IV. Experimental Results

Two kinds of experiments were conducted to evaluate the effectiveness of the intention expression using the robot head. First, when the robot turned around a corner, we evaluated whether it was easy for participants to understand the robot's intentions or not. Next, when a participant and the robot passed each other in a corridor, we evaluated participants' impressions from the robot's motion. The mobile robot shown in Fig. 2 was used in all the experiments.

A. Impression evaluation using videos

A total of ten female and male participants in their twenties and thirties were recruited in this evaluation experiment. Figs. 10 (a) and 10 (b) show the videos of the robot with rotating the head, viewed from front and back respectively. These two videos were connected to one video in this order. Figs. 11 (a) and 11 (b) show the videos of the robot without rotating the head, viewed from front and back respectively. These videos were also connected to one video in this order. These videos were shot in advance before the evaluation experiments, and participant watched them in random order and evaluated the actions of the robot respectively. The length of the video was about one minute and fifteen seconds.

The participants evaluated the understandability of the robot with or without rotating the head in a seven-point scale. The means and standard deviations are shown in Fig. 12. Since the p-value was 0.00057 ($p < 0.01$), these two conditions were significantly different from each other. It can be said that our mobile robot system with the intention expression is better than without the intention expression.



(a) With rotating head(front) (b) With rotating head(rear)

Fig. 10. Videos for impression evaluation

(a) Without rotating head(front) (b) Without rotating head(rear)

Fig. 11. Videos for impression evaluation

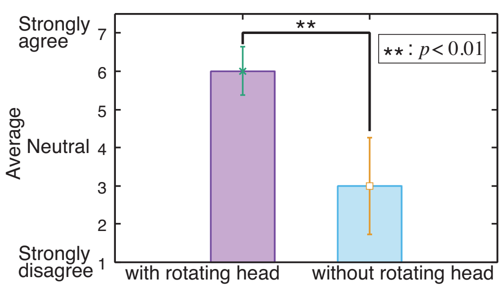


Fig. 12. Evaluation results of understandability with/without rotating head

B. Impression evaluation of passing each other in corridor

A total of twelve female and male participants in their twenties were recruited in this evaluation experiment. Fig. 13 shows the initial positions of a participant and the robot in the corridor. The participant stood opposite to the robot, and they started at the same time when the experimenter signaled them. The maximum speed and angular velocity of the robot were v_{max} = 0.3 [m/s] and ω_{max} = 24 [deg/s] respectively. The constant values included in Eq. (6) were w_{p_x}=1.0, w_{p_y}=4.0, and d_o=1.0. The constant values included in ${}^{r}\boldsymbol{f}$ and ${}^{h}\boldsymbol{f}$ were c_g=1.0, l_g=2.0, c_o=3.0, l_o=0.18, c_p=5.0 and l_p=2.0. In these experiments, when ${}^{h}\boldsymbol{f}$ is calculated,

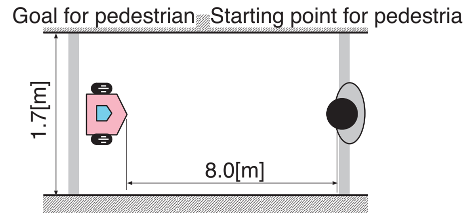


Fig. 13. Experimental environment

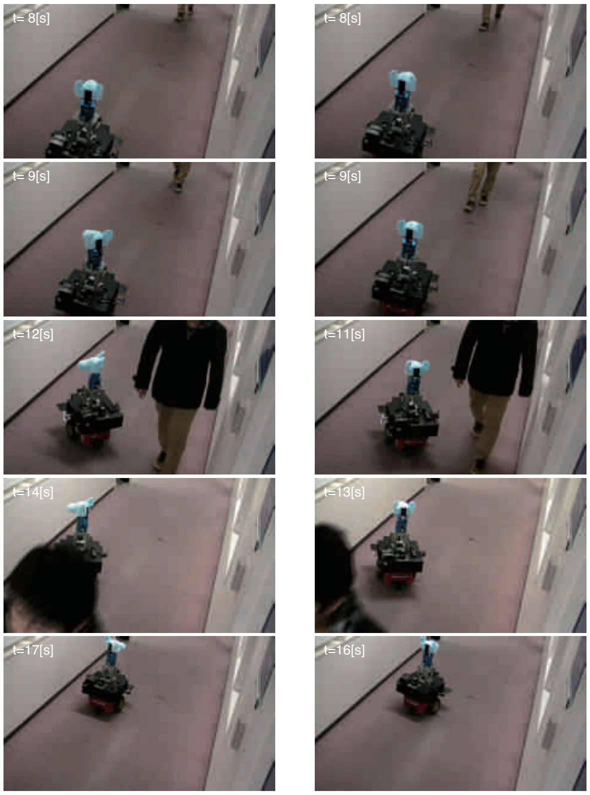
Fig. 14 (a) shows an example where the robot was avoiding the participant while announcing its moving direction using its head. When the robot approached the participant, its head rotated to the robot's moving direction as the intention expression. Fig. 14 (b) shows an example where the robot was avoiding the participant without the intention expression. The head was fixed while driving.

The participants evaluated the understandability of the robot's actions and the easiness of avoidance with or without the intention expression on a seven-point scale respectively. The means and standard deviations are shown in Fig. 15. Since the p-values of the understandability and the easiness were 0.0022 ($p < 0.01$) and 0.00031 ($p < 0.01$) respectively, significant differences were shown in all conditions. It can also be said that our mobile robot system with the intention expression by rotating the head is better than without the intention expression in this experiment.

Next, an impression evaluation using a questionnaire was conducted for investigating what impression the robot behavior gives a person with the twelve participants. Eight adjective pairs shown in Table I were used on seven-point scale. The scores of the positive words on the left side is higher than the score of the negative ones on the right side. As the results of t-test, there were significant differences related to "approachable", "efficient", "active" and "fast", but no significant differences related to "kind", "attentive", "exciting" and "pleasant." In other words, it can be said that the intention expression using the rotational head movement improves people's impression.

TABLE I
MEAN VALUES AND STANDARD DEVIATIONS RELATED TO ADJECTIVE PAIRS

Adjective pair			with		without	
			Mean	SD	Mean	SD
kind	-	unkind	5.25	0.72	4.50	1.19
approachable	-	unapproachable	4.58	1.11	3.83	1.14
attentive	-	inattentive	5.42	0.64	4.67	1.75
efficient	-	inefficient	4.92	0.86	4.00	0.91
active	-	passive	5.83	0.55	3.67	1.31
fast	-	slow	3.58	1.38	2.50	0.87
exciting	-	boring	4.75	1.01	4.08	0.64
pleasant	-	unpleasant	4.33	0.75	3.83	0.37



(a) With rotating head (b) Without rotating head

Fig. 14. Example of experiments in corridor

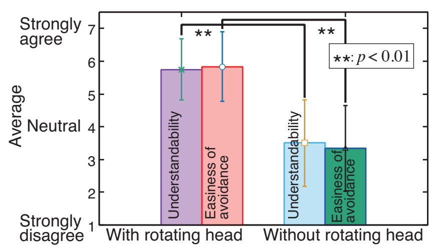


Fig. 15. Evaluation results of understandability and easiness of avoidance with/without rotating head

V. CONCLUSION

We are studying a teleoperated mobile robot that provides useful information to a pedestrian, and have proposed a new intention expression method using the robot head action. When the robot is about to change a moving direction, the robot head is turned to the moving direction in advance of executing a change of the robot's body direction like a human does. The direction of the robot head and the moving direction are determined by an artificial potential field (APF) generated by a control input for teleoperation and positions of pedestrians and obstacles around the robot. The validity and effectiveness of our proposed intention expression method were confirmed with two kinds of experiments.

However, the experimental situation was too simple in this paper. The conflict between the force vector ${}^{r}\boldsymbol{f}$ (or ${}^{h}\boldsymbol{f}$) calculated by the APF and the operator's control input $\boldsymbol{v}_c$ might make some problems under a more complex environment. We will conduct some more experiments to evaluate our method under more realistic environments where there are multiple pedestrians in our future work.

ACKNOWLEDGMENTS

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