Noname manuscript No.
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Guiding a Person through Combined Robotic and Projection Movements

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Received: date / Accepted: date

Abstract This paper proposes a new method that guides humans through an exhibition corridor using a mobile robot mounted with a projector. Conventional guidance delivered by mobile robots is problematic because the robot cannot move when people gather round; alternatively, people may leave the robot and stray from the guidance route. In such cases, the robot must instruct people to move by a vocal or display message such as "Please make way." or "Please come here." Such repeated explicit instructions are uncomfortable to humans. This paper proposes a natural guidance method through a combination of both robotic and projected image movements. The proposed method supposes that human movements are affected not only by the position of the robot but also by the position of the projected image. The proposed method can control the robot and the guided person independently; that is, the robot can move while the guided person remains fixed, or the robot can remain fixed while guiding the person closer. To evaluate the method, the movements of individual 40 participants were monitored under four kinds of guiding behaviors. In these experiments, the proposed method guided each person's positions without issuing explicit instructions.

Keywords Guide robot · Implicit instruction · Mobile robot · Projector

This work was supported by Hiroshima City University Grant for Research Preparation.

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1 Introduction

As robots for daily-life support become more prevalent, they must become more comfortable with people. Besides moving with people, mobile guidance robots must control and guide people without discomfiting them. Guidance is among the most important services of mobile robots in many daily tasks, such as giving explanations and directions in museums [1][2][3][4], hospitals [5][6], and airports[7].

In conventional research and demonstrations of robotic guidance, robots have not exercised proper control of the surrounding humans. It is difficult to move a mobile robot when people gather around it, and a method to deal with this problem by modeling human behavior has been proposed [8][9]. However, it has been reported that the robot cannot move when people block the path of the robot [10]. For example, when too many people gather around the robot, they block the robot's path and the robot cannot move. In other cases, when people leave the guide route, the robot may be unable to return them to the original route. Smart control by conventional guide robots is a difficult task.

To control the movements of surrounding people, conventional guidance robots provide explicit instructions through voices and displays. If too many people gather around a robot, the robot usually issues a voice command [11] such as "Please clear the way." or "Please come here." Other methods explicitly request a human movement by projecting arrows on displays or by pointing a robotic arm in the requested direction. However, such repeated explicit instructions are annoying to humans [12] and cause trouble to those around the robot and passersby [13]. To improve the comfort of the robot guidance, the humans' positions must be naturally controlled and adapted to the situation of the guidance.

In contrast, humans guide other humans in sophisticated ways, using small and comfortable movements and gestures. A function for such natural guidance is also required for guide robots. Akita et al. [14] showed that a robot can guide a person to a comfortable position by slight movements. In an evacuation guidance task, Jiang et al. [15] showed that the movements of a robot affect human behavior, and can realize efficient evacuation. In a guidance task, mobile robots might also control people's movements through implicit guiding behaviors.

This paper focuses on natural guidance by a mobile robot with a projection function. Our guide robot projects an explanation of the exhibition using an onboard projector, and moves the projected image by rotating the projector. To guide a person, we combine two kinds of robot behaviors: robotic movement and projection movement. To guide while explaining exhibits to a person, we propose four guiding behaviors composed of combined robot and projection movements, providing implicit control of the humans' behavior.

The contributions of this paper are as follows:

- We propose a guiding method that combines the robotic and projection movements, and prompts the user to move without issuing explicit instructions.
- We propose not only a method that moves a robot and a person together, but a method that guides a person to remain still while the robot moves, and a method that guides a person to move while the robot remains still.
- We experimentally evaluate the four proposed guiding behaviors and quantitatively clarify the differences in participants' movements using a people-tracking system.

2 Related Work

There have been many studies on using mobile robots to guide people. In this section, we first survey the research on conventional guidance robots (Sect 2.1). Next, we introduce recent studies on mobile robots with projectors and discuss their relation to our research (Sect 2.2). In this paper, we combine these studies and propose a method to provide natural guidance to people. Finally, we also survey studies on the natural influence of mobile robots on human behavior. (Sect 2.3).

2.1 Guide Robots

As a pioneering work on guide robots, Tachi and Komoriya [16] proposed a guide dog robot for the visually impaired. Burgard et al. [1] and Thrun et al. [2] demonstrated a mobile robot that guides visitors through a museum. Since these publications, a tour guide robot [17], a guide robot that effectively uses facial expressions while guiding [18], a shopping support robot [19], and a semi-autonomous guide robot [3] have been proposed. Robots designed for people guidance communicate through various modalities. Kim et al. [20] proposed a guiding robot that makes the appropriate decision through multiple modalities, and directs a movement that fits the situation. Bennewitz et al. [21] proposed a humanoid robot that also uses multiple modalities to communicate with humans. Das et al. [22] proposed a robot that recognizes the social behaviors of humans and takes advantage of these to attract attention.

Research on how to guide humans by multiple robots has also been reported. Martinez-Garcia et al. [23] used multiple robots to surround a crowd of people and guide the group by focusing on the centers of gravity of multiple people. Garrell and Sanfeliu [24] proposed a new model for guiding people in an urban environment using multiple mobile robots by defining robot and human motion with a discrete-time motion model. Shiomi et al. [25] detected people in need of services based on the measurement of their walking speed in a shopping mall and provided services with the cooperation of multiple robots.

These guide robots exploit the tendency of people to follow guide robots. Unfortunately, they cannot control the movements of people around them. For example, when museum visitors gather around the robot, they block its route to the exhibit and hinder its localization [10]. In addition, many people gathered around robots in shopping malls create a nuisance situation [13].

In this paper, we analyze the effects of robotic and projection movements on a guided person, and propose a method that guides different movements of the humans and robot, including those of humans following the robot.

2.2 Projection Robots

Lee [26] equipped a mobile robot with a pan-tilt actuator and a projector that presents the necessary information at any place in the environment. In an experimental evaluation, they guided people by projecting arrows on the ground. Shiotani et al. [27] controlled the robot's movement and projection based on the constraints that consider the distance to the surrounding people and the quality of the projected image. These studies proposed methods to combine the projection from a mobile robot with control using pan-tilt to make the projection easier for people to see. However, when the robot moves while operating the projector, distortion of the projected images becomes a problem. Donner et al. [28] developed a projector-equipped guidance robot that corrects the distortion in the projected images and localizes its self-position. Tatsumoto et al. [29] proposed environmental information structuring in which markers are placed at projectable positions in the environment and a navigation method. Their system continues the projection while the robot is avoiding people and obstacles. These studies proposed an essential function to produce distortion-free human-viewable projections independent of the robot's movement. Mobile robots with projectors have been deployed in various scenarios. Machino et al. [30] proposed a method for efficient and cooperative human-robot working in a remote place using the projection from a robot. Saegusa [31] proposed a walking rehabilitation system using a mobile robot which projects the foot landing position. These studies have proposed various interfaces that combine mobile robots and projectors.

The psychological impact of the use of projection by mobile robots has also been studied. Matsumaru [32] proposed a robot that presents the future positions to the surroundings by projecting its own moving speed and direction onto the floor. Coovert et al. [33] experimentally demonstrated a mobile robot that indicates the moving direction by an arrow pointed on the ground, and investigated whether pedestrians can understand and follow the moving direction. Watanabe et al. [34] proposed a wheelchair robot equipped with a projector that presents the future travel routes. They pointed out the importance of an autonomous mobile wheelchair that shares travel routes with surrounding pedestrians and passengers.

However, none of these studies investigated how the movement of the projection from a mobile robot influences human behavior. Recently, we investigated the effects of both movement and projection by a guide robot equipped with a projector on human behavior [35]. The problem with the study was that the robot could not direct a person's movements while remaining in place, so the distance between the person and the robot was not freely controllable. In addition, the guided person's behavior was not quantitatively assessed by a people-tracking system. Quantitative comparisons between guiding behaviors were also not made. This paper proposes an additional new guiding behavior that guides a person a slight distance from the robot to get closer to it. The four guiding behaviors allow free control of the guided person, which is an important function of guide robots. We also measure the movement of the guided person by a people-tracking system, and quantify the effect of the proposed behavior of the projection robot on the humans' behavior.

2.3 Implicit Guide Robots

Robots are known to influence human behavior without instruction due to their physical presence. Garrell et al. [24] proposed a concept in which one robot leads and the remaining robots surround multiple people like sheepdogs, guiding them without giving instructions. In the field of robotic evacuation guidance, methods have been proposed in which robots can influence the flow of human movement without explicit instructions. Okada and Ando [36] simulated the movement of the crowd based on a vector field model, and proposed a method that arranges the positions of the guides for efficient evacuation. Jiang et al. [15] developed a moving robot system that implicitly guides people through an evacuation zone. Tang et al. [37] proposed a robot-control method that efficiently guides evacuees using a panic propagation model and a social force model. These studies exploit the implicit effect of the presence and movements of inducers and robots on the movements of people. To realize a robot that appropriately shares an environment with people, based on the idea of an implicit rule on a person's relative position [38], Akita et al. [14] proposed a robot that moves to an appropriate relative position after assessing the status of people gathered around a painting.

These studies reported the implicit effects of a robot's position and movement on human behavior. The present paper considers not only the movement of the robot, but also the effect of the movement of a projected image on human behavior. Using a projector for guidance, one can exploit a person's implicit response to the projection, such as the tendency to approach the projected image to view its contents. Combining the robot's position and the projected image, our method properly guides a person along the guiding route in a given situation. It also establishes a natural way of guiding people without repetitive explicit vocal or visual instructions.

3 Guiding Behavior Combined with Robotic and Projection Movement

When a robot guides a person, the robot will not only move with the person but will also need to perform several behaviors according to the guiding situation. We first define the guiding task of the robot in this study (Sect. 3.1), list four guiding behaviors required of guide robots (Sect. 3.2), and propose a method for

Table 1 Basic behaviors of a guide roobot

	The robot moves	The robot stays
Move the target person	A. Ensure that the person follows the robot	B. Guide the person near the robot
Keep the person in place	C. Ensure that the person stays in place	D. Remain with the person

realizing these behaviors with a mobile robot equipped with a projection function (Sect. 3.3). We will also discuss whether the robot can select and guide the appropriate guiding action depending on the situation (Sect 3.4).

3.1 Problem definition

When guiding first-time visitors to museums or companies, a human guide escorts them along the route to their destination while explaining the exhibits and facilities along the way. The proposed robot system performs a similar guiding task. During the guidance, the robot is required to control the position of the guided persons without explicitly instructing them to move.

3.2 Essential Behavior for Guiding a Person

This subsection lists the behaviors required of a guidance robot. The most common behavior of the robot is to move together with the guided person or stay in the same place. In conventional guidance by mobile robots, the guided persons tend to follow the robot or gather around it. However, in some cases, the robot needs to move separately from the human visitors. For example, the robot must secure the movement path in advance while the person viewing the exhibits remains fixed. Alternatively, the guided person may stray from the guidance route. In such a case, the person needs to be guided closer to the robot. Thus, the guiding robot must move both with the person and independently of the person. The four guiding behaviors shown in Table I, which combine the movements of the robot and a person, are expected to achieve a proper guiding robot. The guide robot must perform one of these four types of behaviors to provide appropriate guidance in a given situation.

Thus, the guiding robot not only needs to move with the person together but also needs to move independently. It is considered that the four guiding behaviors shown in Table 1, which combine the robot's movement and the person's movement, are required for guiding robots. The guide robot needs to perform one of four types of behaviors depending on the situation to provide appropriate guidance.

3.3 Guiding Behaviors Combining the Robotic and Projection Movements

Our method combines the robotic and projection movements to realize the four guiding behaviors in Table 1. The robot moves near the exhibit and projects an image with explanatory text below the exhibit. The behavior exhibited by the combined movement and projection is hereafter called the *guiding behavior* of a projection robot. Fig. 1 shows the four guiding behaviors and the expected movements of the guided person. The proposed guiding behaviors guide people by moving the robot and the projected image in the manner shown in Fig. 1 when the robot and the person satisfy certain positional relationships.

Fig. 2 shows the variables used in the explanation. In all guiding behaviors, the robot faces one direction in the corridor and maintains a constant distance from the wall on which the projected image appears. Let the x-axis be the orientation of the robot and d be the distance to the wall. Fig. 2 shows the case where the robot is facing left. Let $\tau = 0[sec]$ be the start time of the guiding behavior, $x_0[m]$ and $p_0[m]$ be the x-coordinates of the robot and the projected image at $\tau = 0$, and x and p be the x-coordinates of the robot and the projected image at $\tau = t$.

In the following explanation, we describe the values of x and p for each guiding behavior. The pan angle $\theta[rad]$ of the projector on the robot is determined from $x[m]$ and $p[m]$ as follows, with $\theta = 0$ when the projector faces the front of the robot.

$$\theta = tan(\frac{x-p}{d}) + \frac{\pi}{2} \tag{1}$$

A. Ensure that the person follows the robot The most common guiding behavior is moving with the person. To realize this guiding behavior, we move both the robot and the projected image in the same direction. When the guided person is near the rear of the robot, the robot and the projected image are moved according to the following equation.

$$x = x_0 + vt \tag{2}$$
$$p = x_0 - a + vt$$

where v is the movement speed in the x-axis direction, and $a[m]$ is a constant for adjusting the position of the projected image to make it easier for the person behind to see it. In the experiment, $a = 0.5[m]$ was used. Because a person tends to follow a robot even in the absence of instruction during the guidance, we expect that the person follows the robot.

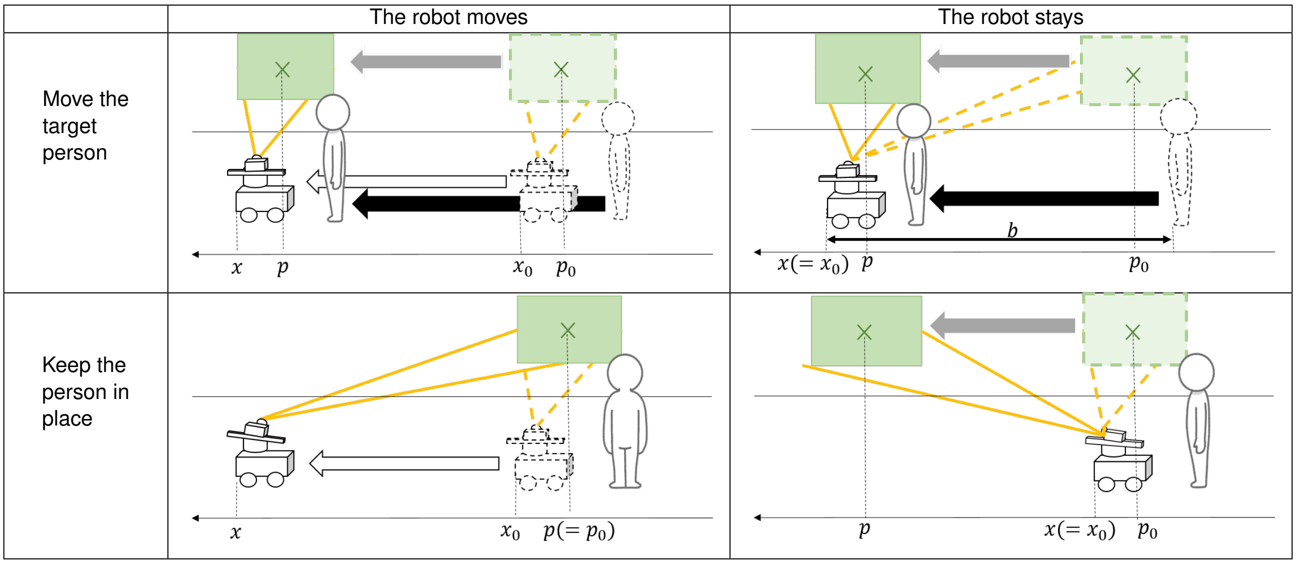


Fig. 1 Guiding behaviors combining the robot movements and projection surface movements.

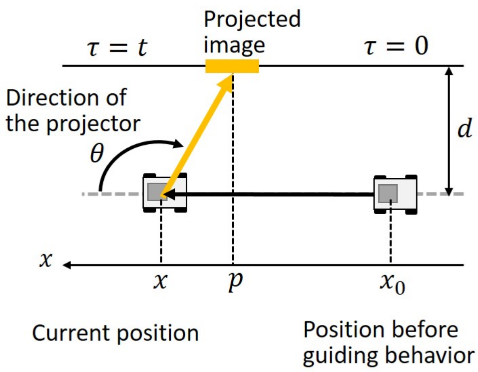


Fig. 2 Positions of the robot and the projected image before and after guiding behaviors

B. Guide the person near the robot When the guided person leaves the route, he or she must be brought closer to the robot on the route. In such cases, the person must approach the robot while the robot remains at one place along the guide route. To realize this guiding action, we move the projected image near the guided person in the direction of the robot. When the person to be guided is located at $x_0 - b$, which is far behind the robot, the projected image is moved according to the following equation.

$$x = x_0 \tag{3}$$
$$p = x_0 - b + vt (p \leq x_0)$$

Note that the projected image stops moving when $t > b/v$ and p does not exceed x. $v[m/s]$ is the speed of movement in the x-axis direction. As people tend to move to where they can easily view the projected contents, we expect that this behavior will draw a person toward the robot.

C. While moving, ensure that the person remains in place The robot must often adjust its position to avoid obstacles or to secure a path for the next move. In such cases, the person should not follow the robot, but should continue viewing the exhibition. Therefore, the person should remain in place while the robot moves. When the person to be guided is near the rear of the robot, the robot is moved according to the following equation.

$$x = x_0 + vt \tag{4}$$
$$p = x_0 - a$$

where, as in the guiding behavior A, $v[m/s]$ is the movement speed in the x-axis direction, and $a[m]$ is a constant. By controlling the direction of the projector, we can maintain a stationary projected image during the robot's movement, which is expected to fix the person at the site of the projected contents.

D. Remain with the person In some cases, the robot must explain an exhibited piece away from the guidance route while the person remains on the route. When the person is near the rear of the robot, the projected image is moved according to the following equation.

$$x = x_0 \tag{5}$$
$$p = x_0 - a + vt$$

where, as in the guiding behavior A, v is the movement speed in the x-axis direction, and a is a constant. As the person is near the robot, we expect the person to remain with the robot when the robot moves the projected image to explain a distant exhibit.

3.4 Selecting a Guiding Behavior in Different Situations

The proposed four guiding behaviors, which combine the robotic and projection movements, are expected to freely control the robot and the person in a given situation. At the time of guidance, the robot decide the appropriate behavior as follows. When the robot needs to move, it selects guiding behavior A or C depending on whether or not it should move with the person. When the robot needs to remain at one place, it selects guidance behavior B or D. To properly guide a person under the selected guiding behavior, the movements of a person must greatly differ in guiding behaviors A and C (or B and D). The following experiments will examine the differences in peoples' movements during these guiding behaviors.

4 Experiments

To confirm the effectiveness of combining the robotic and projection movements, we measured the movements of the guided participants under the four types of proposed guiding behaviors by the robot. We compared and verified the differences among the participants' movements under the different guiding behaviors. In this experiment, the robot did not detect the guided person or plan a route according to the person's location. The robot assumed that a person was at a specific location and performed predetermined guiding behaviors to verify the person's behavior.

4.1 Hypotheses

When guided by a mobile robot, it is reported that they tend to follow the robot and gather around it. Therefore, in guiding behavior A, in which the robot moves both its position and projection, we expect that the guided person will follow the robot. In contrast, in guiding behavior C, the projection is fixed while the robot moves. Given that the projection contains the viewing contents, we expect that the guided person will remain at the place of the projection. Based on these considerations, we formed the following hypothesis:

Hypothesis 1 When the robot moves and the projection is fixed (guiding behavior C), the person is more likely to stay at the current position than when the robot and projection move together (guiding behavior A).

When the robot remains at one place to guide or explain an exhibit, we expect that the guided person will approach the robot because the projected image moves closer to the robot (guiding behavior B). Conversely, when the projected image moves away from the robot (guiding behavior D), we expect that the person will remain with the robot. Based on these considerations, we formed the following hypothesis:

Hypothesis 2 When the projection position shifts away from the robot (guiding behavior D), people are more likely to stay in their current position than when the projection position moves closer to the robot (guiding behavior B).

If Hypotheses 1 and 2 are supported, then human behavior can be controlled by choosing whether or not to move the projection along with the robot. The robot then chooses a guiding behavior that appropriately controls the robot and the person under the guidance expectations, such as following the person, moving away from the person, or guiding a distant person to a close location.

When the projected image moves, the effect of the robot's movement on human behavior is clarified by comparing behaviors A and D.

As people tend to remain close to the robot when receiving guidance, we expect that the guided person will move with the robot when they can clearly see the projected image. Based on these considerations, we formed the following hypothesis:

Hypothesis 3 When the robot remains at one position and moves the projected image away from its body (guiding behavior D), the person will more likely remain at the current position than when the robot moves with the projected image (guiding behavior A).

While the verification of Hypothesis 1 will elucidate the human responses to the projection movements, the verification of Hypothesis 3 will elucidate the responses to the robot movements.

4.2 Experimental Settings

Fig. 3 shows the system configuration of the robot built to verify the guidance method proposed in Section 3. This section explains the robot used in the experiment, the projection position control, and the system that measures the movement of the guided person.

4.2.1 Robot

Fig. 4 shows the mobile robot used in the experiment. A projector (Aigo Projector Cloud PT6316L) is placed on a pan-tilt actuator (TRACKLabs BiclopsPT), which is mounted on a robot cart (T-frog Project robot frame

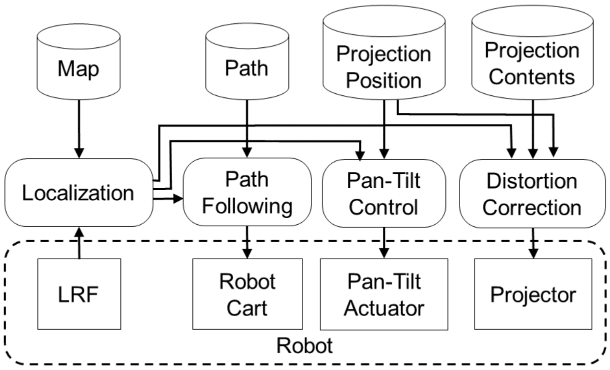


Fig. 3 System Overview

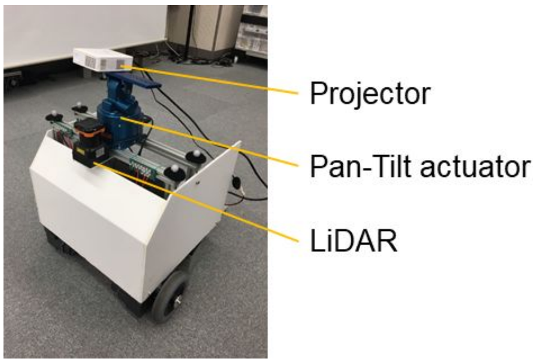


Fig. 4 Projection robot used in the experiment. Independently of the robot's movement, the projector's movement is controlled by the pan-tilt actuator.

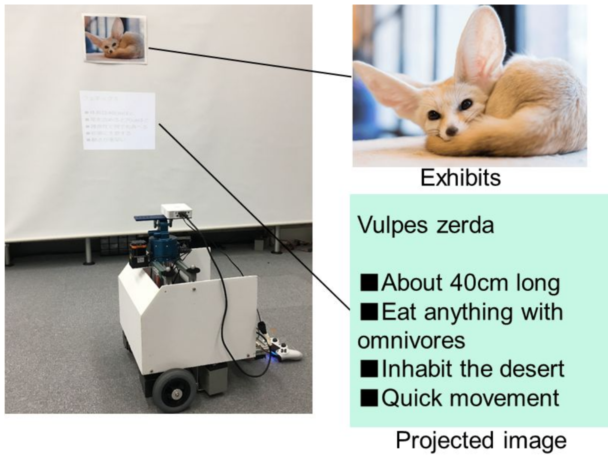


Fig. 5 The robot projects an image with explanatory text. Projections were formed on the wall beneath the displayed photographs.

i-Cart mini). The robot can turn the projector in the vertical and lateral directions. A LiDAR (Hokuyo Automatic UTM-30LX) is mounted at 46 cm above the ground, and the robot localizes its own position by matching the LiDAR observation with the grid map of the environment acquired in advance using a particle filter [39]. The robot autonomously follows a given path. In previous studies, the robot's walking speed was set to slightly slower than the average walking speed of humans (over 1.0 m/s). Pacchierotti et al. set the robot speed to 0.6 m/s [40]. Based on the conventional research, we set the maximum speed of the robot to 0.7 m/s.

4.2.2 Projection position control and image processing

The projections were formed on the wall, immediately below the exhibit to be projected (Fig. 5). The center position of the projected image was 80 cm above the floor. The direction of the projector was determined from the location of the exhibit, which was given in advance on the map, and the estimated position of the robot. The pan-tilt actuator was then controlled to project the image at the calculated position. Distortion in the projection was removed by a deformation process on the projected image, based on the relation between the robot's posture and the projection plane [29].

4.2.3 People Tracking System

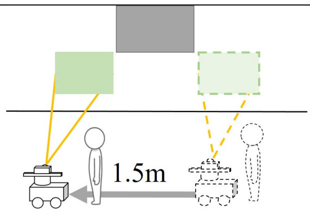
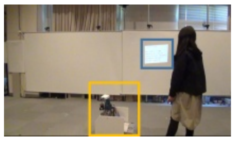
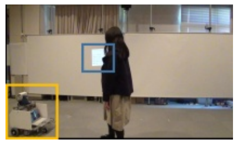
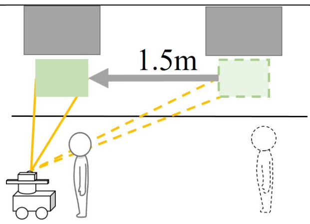
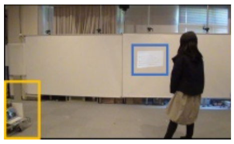
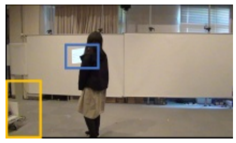
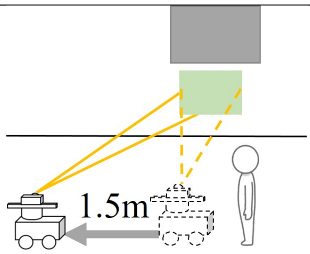
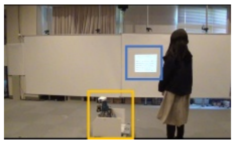
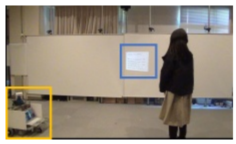
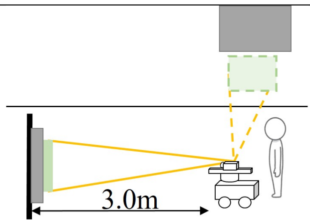
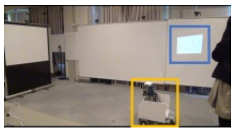
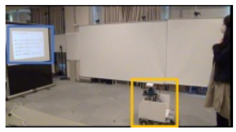
To measure the positions of people surrounding the experimental environment, we installed three LiDARs (UTM-30LX) in the exhibition space. The sensors were placed at 95 cm above the ground, the approximate height of a person's waist and higher than the robot's height. We thus assumed a single moving target in the environment, which could be located at high accuracy. The measurements were performed in two steps: person detection and tracking. The detection step extracted the person's candidate positions by background subtraction and clustering. It then detected an entity of the same size as the person and computed its center of gravity. The tracking step estimated the trajectory of the person using a particle filter. The tracking system computed the smoothed position 20 times in each second.

4.3 Environment

The experiment was conducted in a 2.5 m wide passage (see Fig. 6). A screen was placed on the wall at the right side of the robot's moving direction. Photographs of four different animals were placed at a height of 1.2 m on the wall. The robot was required to explain these exhibits to the experimental participants. The robot moved straight down the corridor, and the route and the corridor wall were separated by 1.7 m.

6

Table 2 Conditions. Four guiding behaviors presented in the experiment.

Condition		Before the behavior	After the behavior
A. The robot and projection moves			
B. The projected image moves			
C. The robot moves			
D. The projected image moves to a distant position			

4.4 Conditions

The above hypotheses were tested under the four guiding behaviors combining the robotic and projection movements. For each guiding behavior, the movements of the participants were measured. Table 2 describes the guiding behavior in each experimental condition and the typical behavior of the guided person. The details of the robot's behavior under each experimental condition are given below.

In condition A, the robot stopped in front of a photograph and began projecting an explanatory image. As the robot moved forward by 1.5 m, the image projected on the screen moved by the same distance.

In condition B, the robot stopped in front of a photograph and began projecting an explanatory image. Remaining stationary, the robot then moved the projected image by 1.5 m.

In condition C, the robot stopped in front of a photograph and began projecting an explanatory image. The robot then moved by 1.5 m without moving the projected image.

In condition D, the robot stopped in front of a photograph and began projecting an explanatory image. Remaining stationary, the robot then moved the pro-

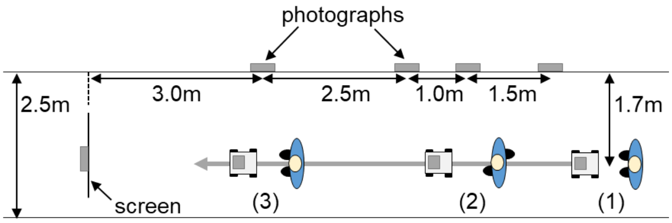


Fig. 6 Experimental environment and movement of the robot. (1) Initial position of the robot and participant. (2) The robot moves to one of the photographs without projecting the exhibit. (3) The robot stops in front of one photograph and begins guiding behavior the participant using the projection.

jected image to the site immediately below the adjacent photograph which is at a distance. As it was difficult to remove distortions in the projection at a steep angle, we projected onto a screen facing the robot in this condition.

4.5 Measurements

The trajectories traveled by the participants during the guiding behavior were measured by a people-tracking system. From the difference in the x coordinate before and after the guidance behavior, we confirmed whether the human participants were influenced by the robotic and projection movements along the corridor direction. To verify the tendency of a person's movement under each guiding behavior, we classified the participants' behavior as *followed* or *stayed* depending on their observed travel distance. Several participants who moved or stayed by only one step were judged as stayed if they moved by less than 80 cm (the approximate human stepping distance).

To evaluate the experimental participants' impressions of the robot's behavior, they rated the following questions on a five-point scale at the end of the experiment. Twenty participants in the latter half of the experiment completed this questionnaire.

- Q1. Did you feel comfortable with the robot guide?
- Q2. Did you find out which exhibit the robot explained?
- Q3. Did you find out which exhibit the robot was leading you to?

4.6 Participants

Forty participants (25 females, 15 males, average age = 23.5 y, SD = 6.1 y) participated in our experiment, all of whom were non-trained volunteers. All experimental procedures were approved by the Ethical Committee of Hiroshima City University (Japan).

4.7 Procedures

After overviewing the experimental procedures, all participants agreed to participate in the experiment. Participants were first familiarized with the robot by watching a guide robot that moved alone and used projections to explain an exhibit. Participants were informed that the autonomous guide robot would use a projector to explain one of four photos on the corridor wall. Participants were requested to partake in four experiments and answer a simple question on the displayed photograph after each experiment. The questions focused on simple attributes of the photographs and were simple enough to be answered just by looking at them, such as "What color was the animal?". Participants were instructed that "the robot will guide you" rather than "please follow the robot". At the beginning of the experiment, the participants and the robot stood at the initial position in the corridor, as shown in Fig. 6 (1). When signaled by the experimenter, the robot began guiding the participants. The robot approached one of the photographs without projecting the image, paused for a few seconds, projected an image with its description beneath the photograph, and performed one of the guiding behaviors. Under condition B, the robot was originally placed in front of the photograph, maintaining constant initial distance between the robot and the person. The projected content was a still image with text describing the animal's name and habitat (see Fig. 5). Participants were sequentially guided under the four conditions described in Table 2, and answered a simple question after each guidance. The photograph described by the robot was varied under each condition, and the order of the four conditions was randomized across participants.

5 Results

In this section, the trajectories of people's movement during the proposed guiding behaviors are shown, and their effect on guiding people is demonstrated (Sect. 5.1). The hypotheses about the proposed method are tested by focusing on the movement of people when they perform different guidance behaviors (Sect. 5.2). The subjective impressions of the proposed guidance method are also presented (Sect. 5.3).

5.1 Overview of the Movement of People

During the experiment, we measured the experimental movements of the participants under the four guiding

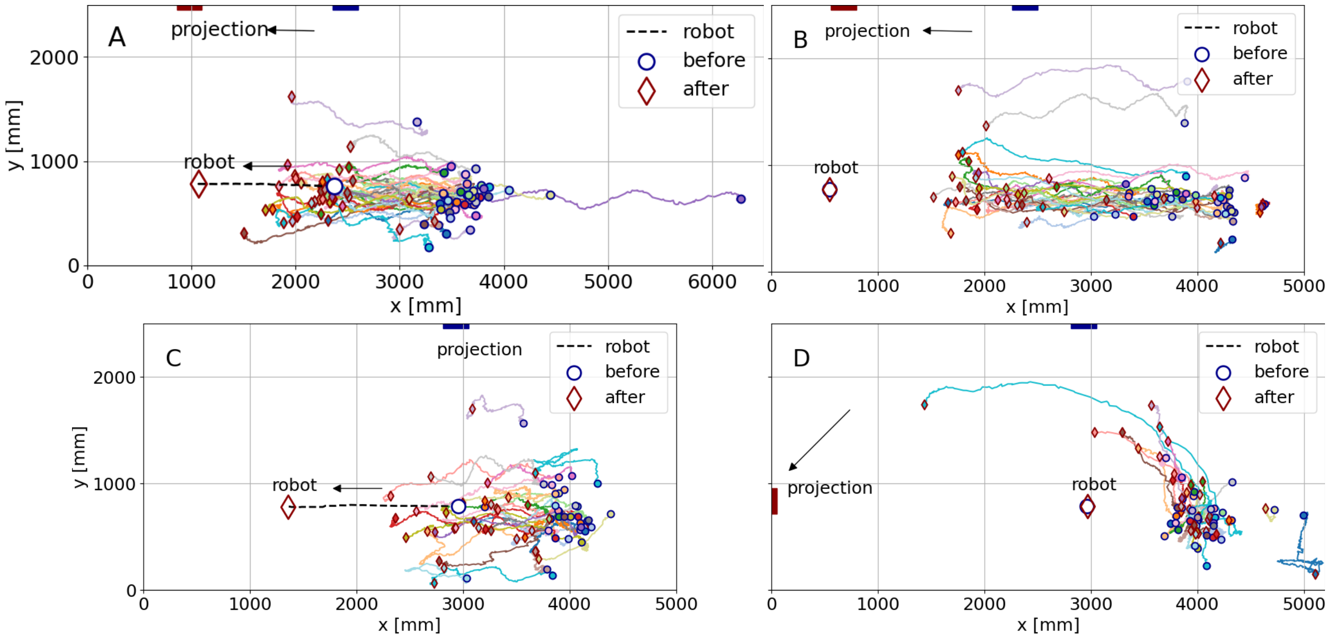


Fig. 7 Measured movement trajectory of the participants

behaviors. The trajectories of the robot and the experimental participants during each guiding behavior are shown in Fig. 7. In this figure, the horizontal axis represents the longitudinal direction of the corridor, and the top and bottom edges represent the corridor walls. Under conditions A, B and C, the robot projected an image on the top wall of the corridor. The robot moved from right to left, paused at the position indicated by the white filled circle in Fig. 7, and began projecting an explanation on the screen. It then performed a guiding behavior, and stopped at the position indicated by the white filled diamond. The dotted lines show the robot's movement path during guiding behaviors A and C. During guiding behaviors B and D, the robot remained fixed. The solid lines show the trajectories of the 20 participants, and the same-color filled circles and diamonds show their positions at the start and finish of the robot's guiding behavior, respectively.

In guiding behavior A, many of the experimental participants closely followed the robot's leftward movement. In guiding behavior B, the robot was stationary but many of the participants moved further to the left, where the projected explanation had shifted. In guiding behavior C, the movement outcomes differed among the participants. Some of the participants were hardly moved by the guiding behavior, while others followed the robot by varying degrees. Many participants moved by a shorter distance than the robot, and several participants moved by only one or two steps. In guiding behavior D, the projected image moved to a slightly distant leftward position shown on the left in the figure. Although a few participants moved to the left by a greater distance than the robot, most of the participants remained at their previous spots.

The measured travel distances of the participants before and after the guiding behavior were calculated and classified as *followed* or *stayed* under the criteria in subsection 4.5. Fig. 8 shows the number of participants classified as followed or stayed under each condition of robot guidance. The behaviors of most participants showed a bias under conditions A, B, and D, and a slightly larger number of participants stayed compared to those who followed the robot in condition C.

5.2 Movement Differences Under the Guide Behaviors

The differences in the numbers of moving people among the guiding behaviors were evaluated in a chi-square test. The percentages of people movements significantly differed between the conditions ($\chi^2(3) = 43.555, p < 0.001$). A pairwise comparison between the conditions was performed at the 95% significance level. Significant differences were detected in the AC, AD, and BD pairs (after Bonferroni correction, AC: $p = 0.011$, AD: $p < 0.001$, BD: $p < 0.001$). These results confirmed that the participants' behaviors were influenced by the guiding behavior, supporting Hypotheses 1, 2 and 3.

Regarding Hypothesis 1, the robot moved away from the participants in guiding behaviors A and C, but the projection was moved and fixed in behaviors A and C, respectively. In behavior A, many participants followed

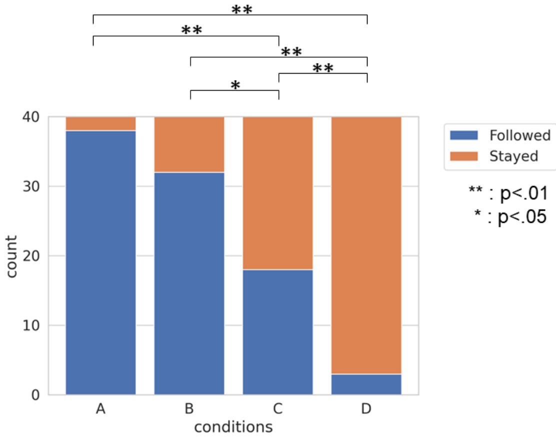


Fig. 8 Behaviors of participants under different robot guide behaviors. Under condition C, half of the participants stopped near the robot.

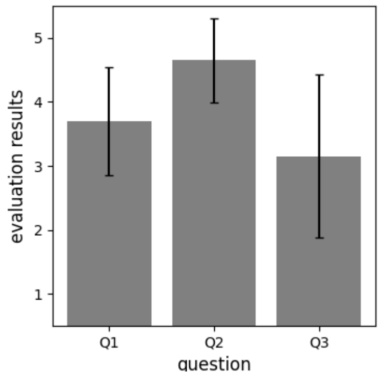


Fig. 9 Results of questionnaire-based survey

the robot and the projection. Conversely, in behavior C, more than half of the participants remained at their previous position. These results demonstrate that when both the projection and the robot moved, the shifted position of the projected image encouraged movement of the participants. Therefore, when the robot is required to move, whether the guided person follows or not can be controlled by appropriately selecting action A or C.

Regarding Hypothesis 2, the robot remained fixed but moved the projected image in guiding behaviors B and D. Recall that the projected image approaches the robot in behavior B, but leaves the robot in behavior D. Consequently, many participants moved along the direction of the projection under behavior B, but remained fixed under behavior D. These results confirm that the response of the guided person depended not only on the position of the robot, but also on the moving direction of the projection.

Regarding Hypothesis 3, the projected image near the participants was moved under guiding behaviors A and D, but the robot was moved and fixed in behaviors A and D, respectively. Many people followed the robot and the projection in behavior A, but remained fixed in behavior D. The differences in human behavior between robot behaviors A and D showed that the participants' movement was affected by the robot's movement even when the projection moved.

5.3 Impressions by participants

Fig. 9 shows the mean evaluation of the robot's behavior. The mean values were 3.7 for Q1 (the comfort of the guide), 4.65 for Q2 (understandability of the subject), and 3.15 for Q3 (understandability of the guidance to the exhibition). The comfort of the guidance in Q1 was relatively high, and the reasons given by those who rated it lower than 2 were that the moving speed of the robot was too slow for two people, the visibility of the projection was poor for one person, and the movement of the projected image was uncomfortable for the guidance action D for one person. As for Q2, most of the respondents answered positively. As for Q3, those who gave a high evaluation in Q3 reported they understood the robot by its stopping position and projection. Those who gave a low rating to Q3 reported that they did not know where the robot was going, that the speed was constant, and that there was no notification.

6 Discussion

Contributions This paper demonstrated that when two actions (movement and projection) are combined on a mobile robot equipped with a projector, the robot can guide a person independently of its own movement. Conventional guidance robots control the gatherers by vocal or other explicit instructions, but the repetition of such instructions is discomfiting to humans. In contrast, our projection robot guides a person naturally by adopting one of four guiding behaviors. We measured the movements of guided persons, and quantitatively showed that the guiding behavior of the robot influences a person's movement. In an experimental evaluation, the proposed method controlled the motions of people around the robot independently of the robot's movement. In particular, the proposed method can avoid crowding around the robot when the robot is required to move, and can gather people closer to the robot when showing an exhibit.

Effects of Projection and Robot Movement on Human Behavior The guided behaviors of many people shown in Fig. 7, can be attributed to the effect of moving the projected image. The guided participants apparently noted the projected explanations and tended to approach the projected position. Comparing the human behaviors under guiding behaviors A and C in Hypothesis 1, we infer that a guided person will more likely be influenced by the projected position than by the robot.

A contrasting situation, in which people did not follow the projection's movement, was also observed. In guiding behavior D, the robot was stationary and moved the projection to the adjacent exhibit in a slightly distant position. In this case, many participants remained near the robot and viewed the projected explanation from a distance. Comparing behaviors A and D in Hypothesis 3, we infer that a guided person will more likely be affected by the robot's position than by the projected image. This result opposes that described in the previous paragraph. The different human behaviors under guiding behavior D might be explained by the ease of viewing the shifted projections. In condition D, we projected onto a screen facing the robot to solve the problem of distortion in the steep angle. The participants may have remained where the projections could be easily seen. The effect of the projection visibility on human behavior must be investigated in future work.

The guided participants' movements might also depend on the positional relationship between the robot, the projected image, and the person. Under guiding behavior D, the movement of the projected image coerced the guided person away from the robot and toward the projected image. Under guiding behavior B, a person approaching the projected image also approached the robot. Comparing behaviors B and D in Hypothesis 2, we infer that a guided person will more likely move toward the robot than to the projection. These results suggest that the positional relationships among the three objects (robot, person and projection) can influence each other when guiding under combined movement and projection. The importance of the positional relationship between robots and humans has been pointed out in may studies [41][42][43]. In this paper, we gained insight into the interaction between the robot, the projected image, and the guided person. However, which factors produce a significant impact has not been clarified here, and requires future investigation.

Impressions by participants Regarding the results of the questionnaire on the impression of the robot, some people pointed out the slow-moving speed of the robot in the comfort of Q1. In contrast, many participants gave a positive evaluation of the robot's movement speed, suggesting the need to adapt the robot to the movement speed of individuals. We believe that the visibility of the projection can be solved by using a projector with higher light intensity. As for Q2, most of the participants had a positive impression about the clarity of the subject matter. As for Q3, most participants answered that the robot was easy to understand after it approached the exhibit, while some participants gave a low evaluation of the ease of understanding during the guidance to the exhibit. Based on the above results, we believe that the proposed guidance did not cause discomfort to most subjects and was accepted by them.

Avoiding congestion around the robot By combining the proposed guiding behaviors, we believe projection robots can guide a person while avoiding crowding around the robot. For example, to keep the person away from congestion, behaviors A and D allow the robot to keep the person close to the robot in the guidance. The guiding behavior C allows the robot to move to avoid crowds while the robot continues to explain the exhibit. Thus, using the fact that the robot's movement and its projection affect the human's movement, the robot can avoid situations where the robot cannot move in a crowded environment.

Influence of robot's size and appearance Robots can strongly attract people by their presence and interaction. It is known that the size of a robot has a significant psychological impact on people. Hiroi et al. [44] compared the impressions of robots of different sizes approaching people and found that smaller sizes were more tolerant of being approached closely. Shiomi et al. [45] compared the effects of different sizes of robots on advertising and reported that people interacted more with the smaller robots. On the other hand, the robot's appearance can also have a significant impact. Humanoid robots have the advantage of being able to present gestures that are easy for people to understand, and the effects of using human-like robots have also been investigated [46]. [45] discussed the effect of size and appearance of robots and found that the effect of size is significant. We also believe that the effect of size is more significant in guiding robots. The investigation of the appropriate size and appearance of the robot combined with the projection function is our future task.

Guiding Multiple People In this paper, we verified that the proposed method can guide one person. In fact, guiding multiple people is an important requirement of guidance robots. For this purpose, multiple people can be controlled as a unified group. Shiomi et al. [47]

pointed out that such robots must attract the attention of the whole group. They proposed a method that controls people's attention by creating situations and contexts through explicit instructions, such as speech. We believe that projecting the explanations (as implemented in the present paper) can also effectively draw people's attention. The combined robot and projection movements can implicitly attract a single person's attention, and should also control the attention of multiple people. When guiding multiple people under the proposed guiding behaviors, the robot and the projected image must be visible to the group members. Based on the position of the guided group, the robot's movement must be planned such that all visitors can observe the robot and/or the projected image depending on the guiding behavior.

Planning the robot's movement to gather multiple visitors into one group is also useful. In [48], multiple people are controlled by multiple robots. The guidance, which is based on the predicted human behavior, attempts to retain people within the group. In single-robot control, the robot's route could be specifically planned to maintain a single group. Projections formed by a mobile robot system can effectively gather people because human movements can be controlled by moving both the projection image and the robot's movement. In subsequent work, we plan to extend these multi-person guidance methods and investigate the effectiveness of the combined movement and projection guiding methods.

Attention of the Guided Person Another factor not considered in the proposed method is the attention paid by the guided person to the projection and the robot. Under the present experimental conditions, most of the guided people focused either on the projection or the robot, probably because the exhibits were displayed only on one wall, and few other objects existed in the experimental environment. In more general environments, the attention of a guided person should be evaluated by measuring the face direction and gaze of the guided person. We believe that the guiding behavior should be appropriately selected to capture the guided person's attention.

7 Conclusion

The proposed method guides people through an exhibition hall using a combination of robotic and projection movements, without explicit instructions from the guiding robot. This paper presents four types of guiding behaviors that combine the movement of the robot with the movement of the projection and proposes a method to control the movement of people around the robot. The movements of the participants in a guiding task through the exhibition corridor were significantly affected by the proposed guiding behaviors. Our next step is to select and execute an appropriate guiding behavior according to the positions of the people around the robot. We would like to realize a guiding robot that adapts the movement of the robot and projection according to human behavior, executes the necessary guiding behaviors, and guides people comfortably to the end.

Conflict of interest

The authors declare that they have no conflict of interest.

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