Investigation of an Autonomous Mobile Robot's Avoidance Motion for Pedestrian and Observer Comfort in a Hospital Environment

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1 Introduction

In recent years, there is a growing demand for autonomous mobile robots to transport medical instruments in hospitals. This is because autonomous mobile robots are expected to improve the quality of medical services by replacing the transportation tasks of medical staff, allowing them to spend their time on more specialized tasks such as keeping an eye on patients and medical examinations[1][2].

For a robot to be accepted by coexisting people, it is important that they feel comfortable about coexisting with the robot [3]. It has been shown that factors related to the robot's motion, such as the robot's motion trajectory and the distance between the robot and humans, have a significant impact on people's comfort [3]-[6]. Therefore, autonomous mobile robots in human coexistence environments need to avoid pedestrians in a comfortable manner.

Specifically, coexisting people can be divided into pedestrians and observers. As a concrete example, Figure 1 shows a pedestrian (a patient) and an observer (a medical staff member keeping an eye on the patient) in a hospital. It is notable that it is important for pedestrians to feel comfortable when they pass by the autonomous mobile robot, and for observers (people who observe the robot's movements from a third-person perspective) to feel comfortable observing the robot's movements. Particularly in hospitals, it is important for medical staff to keep an eye on patients, so it is important for them to have a comfortable impression of the robot's motion when it passes by a patient, in order for the robot to be accepted in the field. Therefore, the aim of this study is to investigate a robot's pedestrian avoidance motion that provides a high level of comfort for both the pedestrian and the observer.

The pedestrian's level of comfort in relation to the robot's motion has been investigated in previous studies. Pacchierotti et al. [7] considered the comfort of a robot's motion when avoiding and passing a pedestrian walking straight along a corridor. They designed an avoidance motion to achieve the desired pedestrian-robot distance when passing a pedestrian, and investigated the pedestrian's level of comfort with respect to

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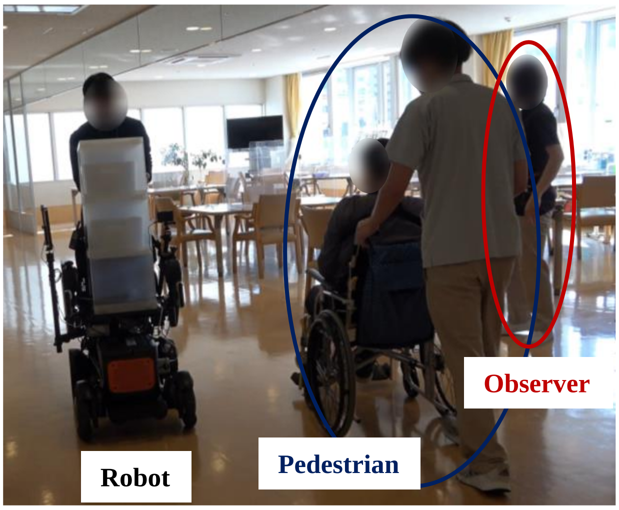


Fig. 1. Pedestrian (patient) and observer (medical staff) in a hospital. It is important for the pedestrian to feel comfortable when they pass by the autonomous robot, and for the observer to feel comfortable when observing the robot's movements.

the distance when passing a pedestrian. They found that the pedestrian's level of comfort decreased when the passing distance was short. Neggers [8] et al. investigated the effects of the distance between the pedestrian and the robot and the speed of the robot on the pedestrian's level of comfort when the robot and the pedestrian pass each other in parallel and in a straight line. They found that the farther the distance between the pedestrian and the robot and the slower the robot's speed, the greater the pedestrian's level of comfort. However, no previous studies have investigated not only pedestrians' but also observers' level of comfort in response to a robot's pedestrian avoidance motion.

Therefore, the aim of this study was to investigate pedestrians and observers in a hospital environment to find out how comfortable they feel with the robot's pedestrian avoidance motion. An experiment was carried out in a hospital to investigate the impression of medical staff on the comfort of the robot's movements from the perspective of pedestrians and observers.

2 Assumed workflow

This chapter describes the assumed workflow when introducing a hospital transport robot and the positioning of this research. First, the medical staff goes to the location where work needs to be done and gives voice instructions to the robot via an intercom about the destination and the item to be transported (e.g. take nappies to room A2). The hospital transport robot uses the staff station as its base, and when it receives instructions from the staff, it moves to the destination where staff are waiting to be transported, such as individual patient rooms, toilets or the linen cupboard for restocking. In the initial phase of operation, it is assumed that the robot will be responsible for transporting nappies and sheets, which do not need to be differentiated for each patient. The workflow described above is expected to eliminate the need for staff to make round trips to transport instruments, allowing them to provide more care and attention to patients, and to improve to a more efficient workflow using a robot.

In the corridor where the robot moves while transporting instruments, it passes pedestrians. This research aims to ensure that the robot's pedestrian avoidance motion when passing pedestrians is highly comfortable to pedestrians and observers.

3 Robot design

3.1 Robot configurations

An overview of the autonomous mobile robot used in this experiment is shown in Figure 2. The robot is a model of the WHILL Model CR [9] electric wheelchair manufactured and sold by WHILL.Inc, to which sensors and computers have been added to enable the acquisition and processing of information necessary for navigation. The added sensors are 2D LiDAR (Hokuyo UST-20LX-H01), 3D Li-DAR (Velodyne VLP-16) and a stereo camera (Intel Realsense D455). The system provides a 360-degree view of the environment by integrating the 3D point cloud information of surrounding obstacles obtained from these sensors. The performance and application of the additional computers were as follows: Lenovo LEGION (Intel Core i7 12700H, 16GB RAM, RTX 3070): for global path planning, Fujitsu LIFEBOOK (Intel Core i7-1355U, 32GB RAM): for planning pedestrian avoidance motion, Jetson AGX Orin: for all other processing.

The pedestrian avoidance motion was planned based on the surrounding obstacle information and the self-position information. The surrounding obstacles was obtained by the 3D point cloud information described above, and the self-position

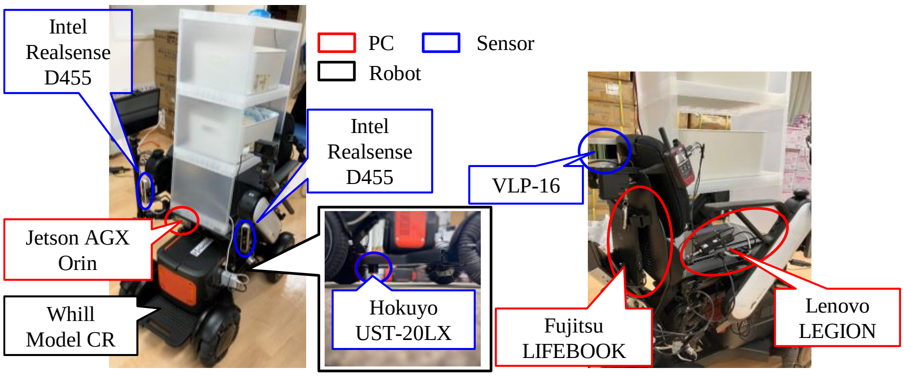


Fig. 2. Hardware configuration of the robot used in the experiment

information was obtained by 3D LiDAR-based self-localization. Details of the pedestrian avoidance motion planning are described in the next section.

3.2 Pedestrian avoidance method

In this study, a method based on state space sampling [10], which is used to generate natural motion that is predictable to humans, is implemented. Specifically, multiple lanes parallel to the global path are defined, multiple candidate lane-changing paths in position space are sampled, and the optimal path is selected. The details are described below.

First, the generation of candidate paths is described. As shown in Figure 3, multiple lanes L parallel to the global path are defined and a lane change path consisting of a clothoid curve is generated for each lane. Each lane is generated at intervals of Δl [m] until the change distance from the global path is l_{max} [m]. The approximate shape of the lane change path is determined by the forward distance $d_{forward}$ [m] and the change distance l_{change} [m] shown in Figure 3. The lane change paths and lanes are then discretized into a sequence of points and combined to generate a candidate path P_i.

Next, the selection of the optimal candidate path and the calculation of the speed command value are explained. Select a candidate path P_i^* that minimizes the following evaluation function J_i.

$$
\begin{aligned}
J_i &= w_{goal}\left(d_{goal,i} - d_{col,i}\right) + w_{lane}\, d_{lane,i} \Big/ \max_{i \in L}\left(d_{lane,i}\right) \\
P_i^* &= \arg\min_{i \in L} J_i
\end{aligned}
\tag{1}
$$

where $d_{goal,i}$ is the distance to the goal of P_i, $d_{col,i}$ is the distance to collision with an obstacle on P_i, $d_{lane,i}$ is the distance between the lane of P_i and the current lane, and w_{goal}, w_{lane} are the weights. Therefore, the candidate path that is most progressive towards the goal, i.e. avoids pedestrians and changes to the nearest lane is selected. The selected path is then followed by the Pure Pursuit algorithm [11] to calculate the speed command values.

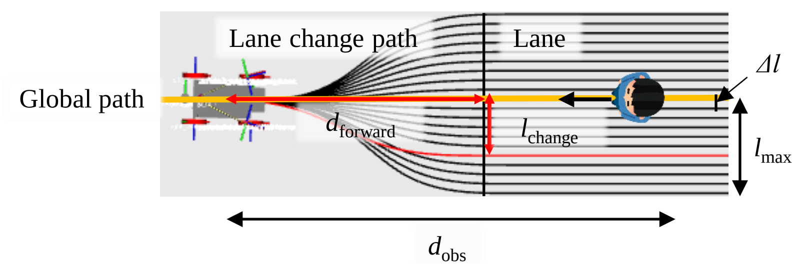


Fig. 3. Parameters of the pedestrian avoidance motion

3.3 Robot motion in the experiment

In this experiment, the robot and the pedestrian first faced each other and started moving simultaneously. Then the pedestrian and the robot moved straight ahead, and when the distance between the pedestrian and the robot became smaller than the avoidance start distance d_{obs} [m], the robot changed to a lane where the pedestrian could be avoided based on the pedestrian avoidance method described above, and passed each other.

4 User study design

In this section, the design of the subject experiments is described. The experiment was approved by the Bioethics Committee of the Faculty of Science and Technology, Keio University. Approval No. 2023-030.

The experiment was conducted in the space in front of the staff station on the 6th floor (hospital floor) of the Nagasaki Rehabilitation Hospital [12]. Six medical staff (two males and four females) participated in the experiment. The six subjects are referred to as M1, M2, F1, F2, F3, and F4, respectively.

The experimental scene is shown in Figure 4. As shown in Figure. 4, a medical staff member passed the robot as a pedestrian and a medical staff member observed the robot's pedestrian avoidance motion as an observer. The pedestrian and observer were each asked about their level of comfort with the robot's pedestrian avoidance motion.

The experimental procedure is described below. The experiment was conducted by two staff members: one who participated in all the experiments (M2) and a newly called staff member (P: M1, F1~F4). The experiment was conducted as follows: after calling P, P was asked to pass the robot and P was asked about his/her level of comfort from the pedestrian's point of view and M2 was asked about his level of comfort from the observer's point of view. Next, P was asked to observe the robot passing M2 at the moved position, and the level of comfort from the observer's perspective was heard from P and the from the pedestrian's perspective was heard from M2. The experimental design of the robot moving back and forth reduced the time required to position the robot and was therefore designed to be friendly to the medical staff on duty. The time required per person was set at 15 minutes and the number of trials was flexibly increased or decreased depending on the remaining time and the experimental situation. The robot's motion parameters were those given in Table 1, where v_{max} is the maximum translational velocity, a_{max} is the maximum translational acceleration, ω_{max} is the maximum angular velocity, α_{max} is the maximum angular acceleration and f is the control frequency.

The evaluation indices are described below. In this study, the level of comfort with the robot's motion was assessed using a 7-point Likert scale questionnaire. Specifically, for the question "I feel comfortable in the robot's motion", "I feel comfortable" was set to 1 and "I do not feel comfortable" was set to 7.

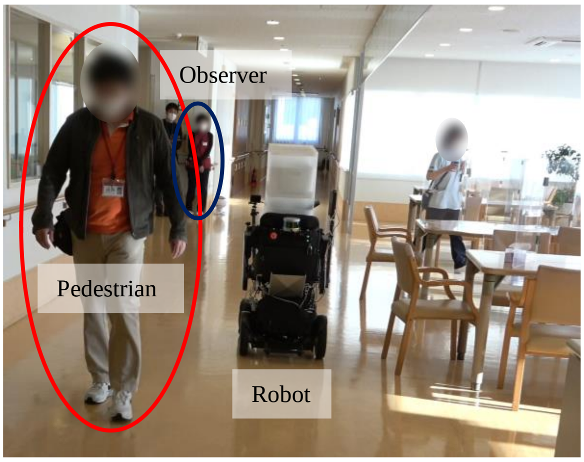


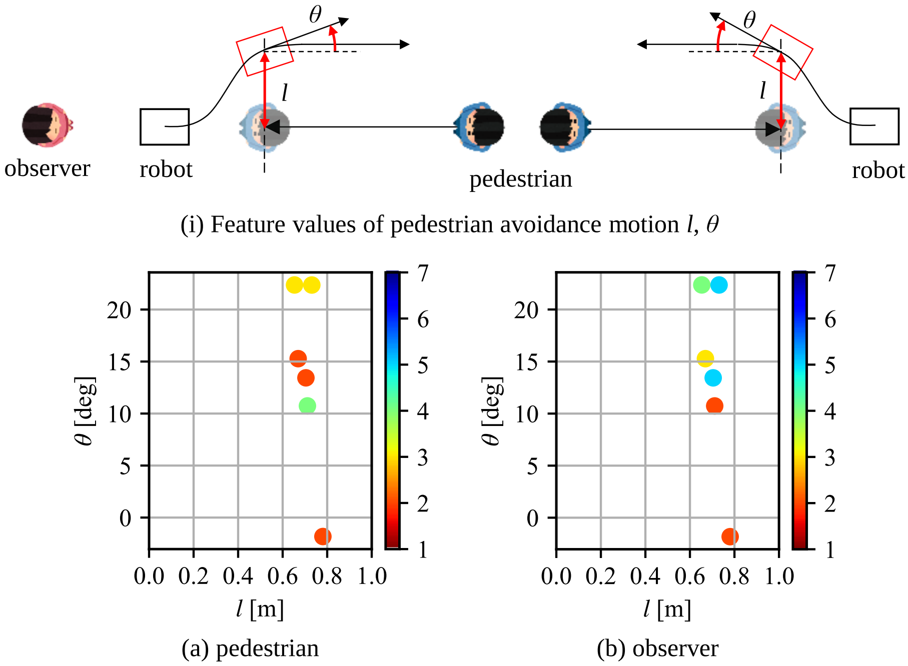
Fig. 4. Experimental scene

Table 1. Parameters used in the experiment

Parameter	Value	Parameter	Value
Δl [m]	0.10	α_{max} [rad/s^2]	0.80
l_{max} [m]	1.0	d_{obs} [m]	10.0
$d_{forward}$ [m]	2.0	w_{goal}	2.0
v_{max} [m/s]	0.50	w_{lane}	8.0
a_{max} [m/s^2]	0.80	f [Hz]	20
ω_{max} [rad/s]	0.40	-	-

5 Results and discussions

In this experiment, a total of ten passing movements were performed and analysis was performed on a total of six data sets, excluding one data set in which the subject had to repeat the evaluation and three data sets in which the robot's motion became oscillatory before the passing movement was performed and the level of comfort evaluation for the pedestrian avoidance motion could not be obtained. When analyzing the relationship between the robot's pedestrian avoidance motion and the level of comfort evaluation of the pedestrian and the observer, the distance l between the pedestrian and the robot and the robot's pose angle θ when the pedestrian and the robot pass each other are taken as the feature values of the pedestrian avoidance motion, as shown in Figure 5 (i). The reason is that l is an index that has been investigated in previous studies to evaluate the level of comfort of mobile robot motion, and θ represents the progress of the pedestrian avoidance motion. When θ is large, the robot is changing lanes, and when θ is close to 0, the robot is following a lane.



(i) Feature values of pedestrian avoidance motion l, θ

(a) pedestrian

(b) observer

(ii) l-θ plot of questionnaire

Fig. 5. Relationships between questionnaire and robot pose θ, distance l

Figures 5 (ii)-(a) and (b) show scatter plots representing the level of comfort of pedestrians and observers for l and θ. It can be seen that for both pedestrians and observers, especially for observers, a point of low level of comfort occurs when θ is large. Note that a large θ indicates that the pedestrians have passed each other during a lane change. Since the value of l does not change much in any trial, i.e. when passing during a lane change, the pedestrians' and observers' level of comfort tends to decrease when θ is large, regardless of the value of l. This result suggests that it is important not only to increase the distance between the robot and the pedestrian when passing as the previous studies have shown, but also to design the robot to pass the pedestrian after the lane change.

6 Conclusion

This study investigated the pedestrian avoidance motion of an autonomous mobile robot with a high level of comfort. In particular, because it is important for medical staff to keep an eye on patients, the level of comfort was studied not only from the perspective of the pedestrian, which has already been studied, but also from the perspective of the observer, who observes the robot's movements from a third-person perspective. The experiment was conducted in a real hospital, where medical staff were asked about their level of comfort from the pedestrian's and observer's perspective in relation to the robot's pedestrian avoidance motion. The level of comfort of the robot's pedestrian avoidance motion was analyzed by examining the relationship between the feature values of the pedestrian-robot distance l and the robot pose angle θ as the pedestrian and the robot passed each other. While the value of l did not change much in any trial, impression of low comfort was observed for both pedestrians and observers, especially for observers, as θ increased. That is, when passing each other during a lane change, the comfort of the pedestrian and the observer tended to decrease regardless of the pedestrian-robot distance.

In the future, we would like to develop a pedestrian avoidance method designed to pass pedestrians after a lane change. In addition, we would like to conduct a demonstration experiment in which medical staff collaborate with a hospital transport robot in a hospital, and investigate changes in medical staff workflow as a result of the introduction of a hospital transport robot.

Acknowledgments

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