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Communicating Robotic Navigational Intentions

Atsushi Watanabe[1], Tetsushi Ikeda[1], Yoichi Morales[1],
Kazuhiko Shinozawa[2,1], Takahiro Miyashita[1] and Norihiro Hagita[1]

***Abstract*— This paper presents a study on intention communication in a navigational context using a robotic wheelchair. The robotic wheelchair uses light projection to communicate its motion intentions. The novelty of the work is threefold: the communication of robot intentions to the passenger, the consideration of passenger and robot as a group ("in-group") [1] who share motion intentions and the communication of the in-group intentions to other pedestrians (the "out-group"). A comparison in an autonomous navigation task where the robotic wheelchair autonomously navigates the environment with and without intention communication was performed showing that passengers and walking people found intention communication intuitive and helpful for passing by actions. Evaluation results significantly show human participant preference for having navigational intention communication for the wheelchair passenger and the person passing by it. Quantitative results show the motion of the person passing by the wheelchair with intention communication was significantly smoother compared to without intention communication.**

Fig. 1: An example of a robotic wheelchair with a light based navigational intention projector showing the trajectory that they are about to take

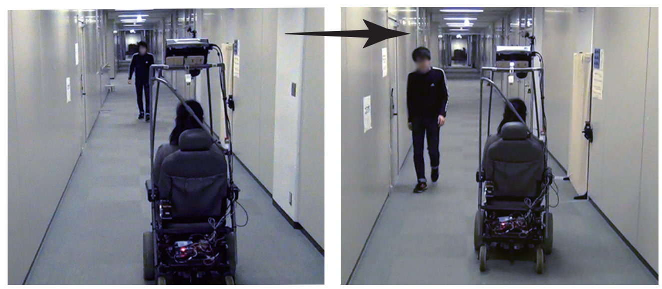


Fig. 2: An example of a robotic wheelchair facing a pedestrian without social cues

I. Introduction

Robotic wheelchairs availability is likely to increase and benefit large parts of aging population as independent mobility plays a pivotal role in aging [2]. Wheelchairs are required to be free from collisions and comfortable for the passengers and people around. Robot navigation between people has received large attention by the scientific community given the increasing availability of robots in real environments. Navigation between people is a difficult task given the complexity of human behavior and walking patterns [3]. Humans engage in joint collision avoidance adapting their trajectories to each other making room for navigation [4]. To adapt their trajectories humans communicate their intentions of walking motion using different types of cues such as gazing and following a pattern of direction of movement.

Robot motion readability is important to display its current state [5] and prevent humans of its motions. Giving social cues from the robot to the human for navigation behaviors is not a trivial task given the lack of capacity of proper communication; misused social cues could lead to humans misunderstanding robots intentions [6].

An intention is a plan of action in pursuit of a goal, they are predictive and precede actions [7] [8]. This work points out the importance of navigational intention communication for natural passing by behavior resulting in comfortable navigation for the passenger riding a robotic wheelchair and people passing by. In this paper the term intention is used in a navigational context referring to the plans of action towards a goal by the the robotic wheelchair and the passenger.

For a robotic vehicle, robot navigation results as consequence of passenger intention to go a destination. In this case the passenger and the robot form a group ("in-group" [1]) where the robot has to plan and communicate its motions satisfying the passenger and people around (out-group). Proper communication of robot future motion to the passenger allows him/her to expect their future motion and be comfortable even when passing close to walls. Moreover, robot motion perception by the out-group is important because improper or dangerous motions by the in-group results in passenger discomfort. Even in the absence of pedestrians in the environment, passengers care about the possibility of disturbing humans choosing to stay at a side of the path [9].

Figures 1 and 2 show a human passenger riding a robotic wheelchair with human detection and avoiding capabilities when facing a pedestrian in a hallway. Figure 1 shows an example of the robotic wheelchair with a light based intention projection showing the future motion (path trajectory) that the in-group is about to take. The pedestrian sees the

* This work was supported by JSPS KAKENHI Grant Number 25330314.
[1] All the authors are with the Intelligent Robotics and Communication Laboratories, Advanced Telecommunications Research Institute International, Japan atsushi.w@ieee.org
[2] Kazuhiko Shinozawa is with the Osaka Kyoiku University, Japan

light, understands the motion cue of the wheelchair and takes the other side of the corridor resulting in natural passing by interaction. In this case the projection is helpful for the pedestrian to understand the in-group avoidance motion and for the passenger to indicate where and how are they heading. Figure 2 shows the robotic wheelchair detecting and avoiding a human in a hallway without social cues. Even if the robot detected the person and is planning to avoid him/her, he/she is unaware of this. The lack of availability of robot motion cue results in having the pedestrian guessing the intention of the wheelchair and having him/her to perform a delayed avoidance maneuver producing in a non-smooth passing by interaction. In this case, the passenger is uneasy observing the awkward interaction.

This work proposes an approach to show robot's navigational intentions with a projector emitting light on a common global coordinate frame. The information projected on the environment signals the future motion intentions of the in-group to the out-group resulting in smooth passing by interaction between the in-group and the out-group. This interaction results in navigational comfort for the passenger and keeps the walking comfort of pedestrians.

II. Related Works

A. Intention Communication

There have been works using light projectors in mobile robots without passengers [10]. For example, the work in [11], presented a robot system with a projector showing the robot operation with colored arrows, in [10] a light emitting approach to indicate robot's direction of motion was proposed. Differently from these works, this paper presents a human-robot system which shows robot intention for the robot user and other humans around. Section IV presents the proposed system to express information for the in-group and a walking pedestrian.

B. Robotic Wheelchairs

The work in [12] proposed a robotic wheelchair that estimates intended direction using passenger's face direction detected by image processing and environmental information. A visual interface to recognize command request of a person from head movements was proposed in [13] where rotation and vertical motion to indicate intent of direction and speed respectively. A single robotic wheelchair moving with multiple companions was presented in [14]. For dynamic environments the work in [15] presents an approach to smoothly handle moving obstacles in a corridor. There are also works regarding robotic wheelchair passenger comfort considerations. A model of passenger environmental visibility was presented in [16], in another work human factors were considered for computing comfortable paths [17] and in [18] a model of human habituation to select proper robot velocity was proposed.

The work in this paper is implemented on a robotic wheelchair and evaluated with human participants. Differently from other works, this paper presents a study and an evaluation of robot intention communication to the human passenger and a pedestrian in the environment.

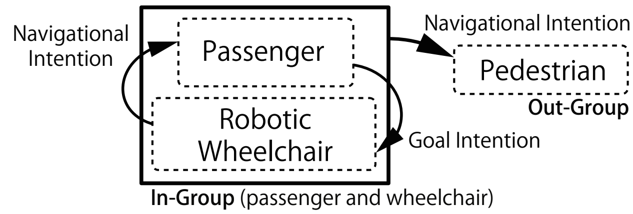


Fig. 3: Concept of navigational intention communication and group forming. The passenger communicates his goal to the wheelchair and the robotic wheelchair communicates its navigational intention to the passenger and people around them. Loop of intention between the passenger and the wheelchair forms the "in-group".

III. Robot Navigational Intention Communication and Group Forming

This section provides a definition of robot navigational intention and its communication importance for human-robot interaction is explained. The concept of group forming for intention communication is also described.

A. Intention Communication

An intention is a plan of action in pursuit of a goal, thus, it includes an action plan and a goal. The understanding of intentions is fundamental because it provides the interpretation of the current activity. Having the capacity to form intentions (and communicate them) allow coordinated actions over time [19]. In the case of human-robot interaction, the communication of robot intentions is a complicated task given the limitations of robot's computation capabilities and adequate hardware to provide understandable social cues.

This paper studies the intention communication of a robotic wheelchair. The robot main activity is the transportation of a human passenger, thus, autonomous navigation to a goal location. In a navigational context, the robot has to offer safe and comfortable navigation to the passenger while negotiating traffic with pedestrians. In order to keep people comfortable, besides navigating at reasonable velocities avoiding sudden movements, the robot has to provide readable motions, i.e., it has to communicate its navigational intentions.

There are three different flows of communication in a passenger-wheelchair-pedestrian scenario as indicated by arrows in Figure 3. **i)** The passenger communication of his intended goal to the robotic wheelchair (i.e., by speech [20] or brain machine interfaces [21]). **ii)** The robotic wheelchair navigational intentions communication to the passenger. **iii)** The communication of the passenger and wheelchair intentions to pedestrian(s) in the environment.

B. Group Formation

Group formation becomes an important concept in intention communication. Robotic wheelchairs provide mobility to passengers, in this case, the robot becomes an extension

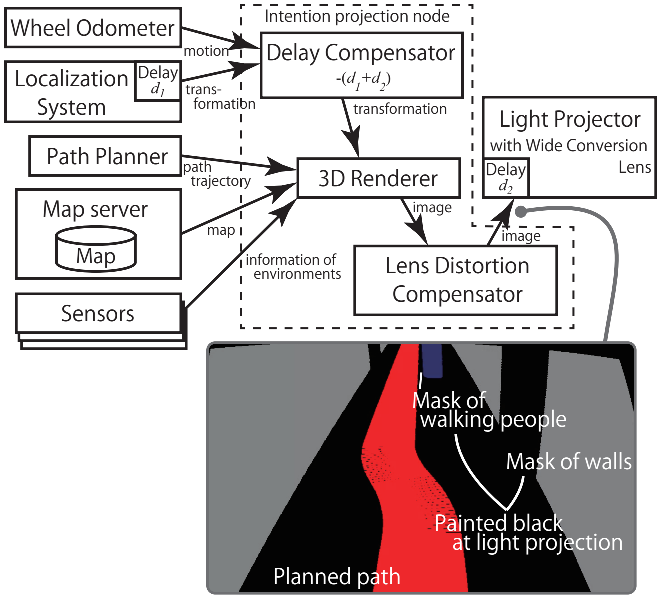


Fig. 4: System structure of navigational intention projection for autonomous robotic wheelchair

Fig. 5: Practical hardware configuration of the robotic wheelchair with light projector

to the passenger. Passenger and robotic wheelchair become a group when interacting with other people named "in-group" [1] as illustrated on the left side of Figure 3.

From the in-group point of view, pedestrians around them are perceived as strangers who form the "out-group". The out-group is formed by one or more pedestrians around. In this paper the out-group is formed by a single walking person as shown on the right side of Figure 3.

The relation between the in-group and the out-group plays an important role for the passenger comfort. If the robotic wheelchair produces motions that disturb the out-group making them uncomfortable, the ride becomes uncomfortable for the passenger as he/she feels empathy for the out-group (even if robotic wheelchair was initially comfortable for the passenger). To avoid this situation the wheelchair has to provide useful social cues for the passenger and the out-group to engage in mutually understandable and natural interactions. Wheelchair communication is performed using the projection mapping approach explained in Section IV.

IV. Projection Mapping Robotic Wheelchair

This section presents the projection mapping robotic wheelchair system, which provides navigational intention communication to its passenger and people around.

A. Navigational Intention Projection

As indicated in the previous section, it is important for a robotic wheelchair to communicate its navigational intentions for both, the passenger and the out-group. In this work the authors chose to use light projection to show navigational intentions because it can communicate robot's future intended trajectories in a visible way to the passenger and the out-group. The rest of the section describes the projection mapping approach utilized to provide a global consistent view around the wheelchair.

Figure 4 shows a system structure of the navigational intentions projection. Wheelchair's future motion information has to be shown on a common coordinate frame. The coordinate system shared by the robot, passenger and out-group is the surrounding environment. The wheelchair has a pre-built grid map of the environment, it localizes, plans and navigates on it. Robot trajectories are planned on world coordinates and can be simply transformed be projected on the environment surface. The system was implemented on ROS [22] framework. For path planning and navigation newly developed utilities were utilized.

To cope with delay from data transfer in the software framework around localization system and light projector, a delay compensator predicts future pose of the wheelchair by linear extrapolation. As light projector delay is constant only the localization transformation delay is calculated from the time stamp of the data and utilized to render the projected image of the planned path trajectory. A part of the trajectory might be hidden by walls and objects around the robot including walking people, it is masked by a three-dimensional model reconstructed from the map and sensor data to prevent inconsistent projections. The image is distorted according to the inverse lens model represented by a cubic polynomial to present consistent transformation. With this process, the projected image fits real environment through wide conversion lens.

B. The Robotic Wheelchair

A differential drive powered wheelchair with wheel encoders attached to the motors was used as platform. The robotic wheelchair has a roll bar like frame and a LCD light projector over passenger's head as shown in Figure 5. Wide conversion lens are used to cover the wide field of projection in front of the projector. Power for the projector is supplied

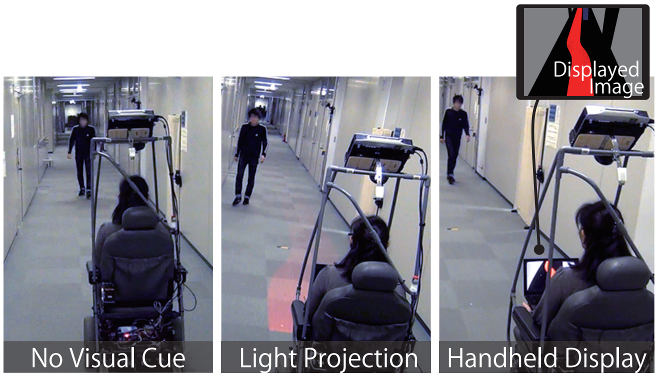


Fig. 6: Conditions of navigational intention communication in experiments: no visual cue, light projection of the wheelchair's future trajectory, and displaying on the hand-held display.

from wheelchair's battery through a DC-AC converter. The wheelchair has one Hokuyo UTM-30LX LIDAR for localization and collision prevention.

C. Motion Controller

The intention projection wheelchair is based on ROS framework. To have consistent and reproducible runs, the authors implemented a motion controller ROS node that the authors named "trajectory tracker" and used it instead to follow planned paths. [1]

This module controls angular velocity of the robot to follow a given path trajectory based on [24].

V. Experimental Procedure and Evaluation

This section explains the experimental procedure and the evaluation between three different conditions: No intentional social cue, the use of the projection mapping method of Section IV and a handheld display device showing the same information of the projector.

The authors performed experiments with 16 human participants asking them how comfortable and how easy was to understand the movement of the wheelchair through a questionnaire.

A. Experimental Procedure

This section explains the experimental evaluation of a robotic wheelchair passing by a single pedestrian in an indoor hallway.

Experiments were performed with eight pairs of 16 Japanese participants, 10 female and 6 men with ages from 23 to 47 with average age 36.5. Figure 7 shows the geometric configuration of the experimental environment consisting of a straight indoor corridor.

Each experiment evaluated a pair of participants at a time. The experimental scenario was that of a person sitting on the robotic wheelchair as a passenger and the other as a walking pedestrian. The participants were told that the wheelchair sometimes inform its future trajectory by using projection on the floor or the hand held display. The order of the experimental conditions was not told to them. The passenger was told that the wheelchair was taking him/her to the end of the corridor and the pedestrian was asked to walk to the end of the corridor. The wheelchair started at one end of the corridor and the pedestrian at the other one as they moved towards each other passing by themselves.

The wheelchair follows a straight line at the beginning and generates a path trajectory to avoid 0.3 m to the opposite side of the person when the distance between them is less than 10 m as shown in Figure 7.

Three different approaches were compared (Figure 6):

- No visual cue.
- Light projection of the wheelchair's future trajectory.
- Displaying the wheelchair's future trajectory on a hand held display.

The experiment for each pair of participants was done in the following fixed sequence:

- a round trip without a visual cue
- a round trip with light projection
- a round trip with displaying at hand

To simulate realistic passing by conditions after they habituated, participants were asked to observe the other participant to prevent them from paying too much attention to the projected or displayed information. After each run, they answered a questionnaire. After finishing the sequence, the pair of participants rotated their roles.

Path trajectories of pedestrians in the experimental environment were observed to perform quantitative evaluate of walking person behavior. The authors installed a sensor network consisting of four Hokuyo UTM-30LX LIDARs at a height of 85 cm (Figure 7). The position of each pedestrian in the corridor was computed based on a particle filter based algorithm by using torso-level scan data from the LIDARs [25]. These position data is also delivered to the wheelchair to mask the projected path hidden by the pedestrians.

B. Evaluation

After each run the authors gave participants a questionnaire asking passenger to rate several things:

1) for wheelchair passengers
   1 Comfortability
   2 Easiness to understand the movement of the wheelchair
   3 Impression of comfortability of the person passing
   4 Easiness to understand the movement of the person passing
2) for walking people
   1 Comfortability
   2 Impression of comfortability of the person passing
   3 Easiness to understand the movement of the wheelchair

The questionnaires had a Likert scale from a 1 to 5 with lower values representing higher scores.

[1]The trajectory tracker source code is implemented in ROS framework and available at: (`https://github.com/at-wat/trajectory_tracker.git`).

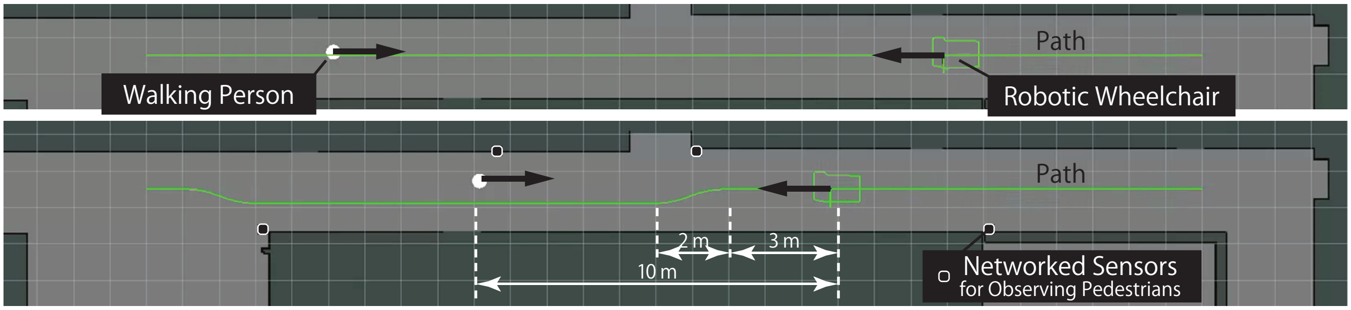
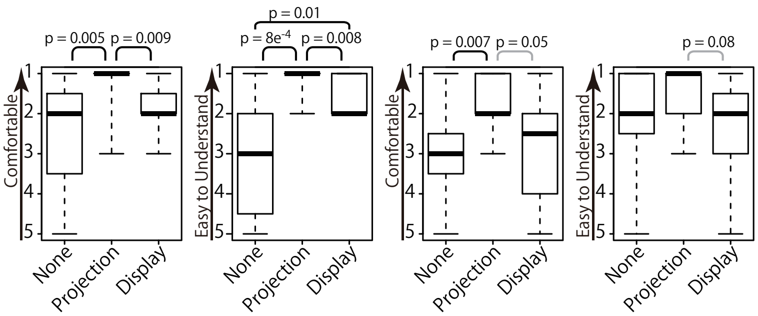
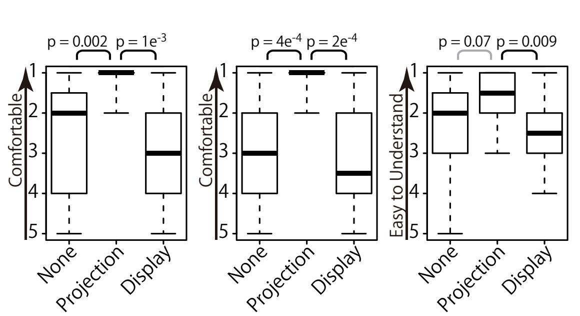


Fig. 7: Geometric configuration of the experiments on a straight corridor



(a) Comfortability (b) Intelligibility of wheelchair's motion (c) Observation of walking person's Comfortability (d) Intelligibility of walking person's motion

Fig. 8: Statistical analysis result of questionnaire for the wheelchair's passenger



(a) Comfortability (b) Observation of passenger's Comfortability (c) Intelligibility of the wheelchair's motion

Fig. 9: Statistical analysis result of questionnaire for passing person by the wheelchair

Experimental results of questionnaires for passenger of the wheelchair are shown in Figures 8a–8d. The results are analyzed by Steel-Dwass' non-parametric multiple comparison tests. It is statistically significant ($p < 0.05$) that passenger's comfortability with projection is better than without visual cues and with hand-held display. The order of easiness to understand wheelchair's motion with the easier one first is with projection, hand-held display, and no visual cue.

It is also statistically significant that passenger looked passing person was comfortable with projection compared to no visual cue. It is marginally significant ($p < 0.1$) that passenger looked passing person was comfortable, and passengers are easy to understand passing person's motion with projection compared to with hand-held display.

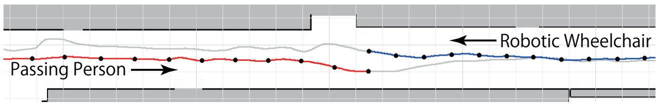
Experimental results of questionnaires for passing person are shown in Figures 9a–9c. It is statistically significant that passing person's comfortability and observed comfortability of passenger of the wheelchair with projection is better than without visual cues and with hand-held display. Easiness to understand wheelchair's motion with projection is statistically significant compared to with hand-held display, and marginally significant compared to without visual cue.

C. Analysis of observed human trajectories

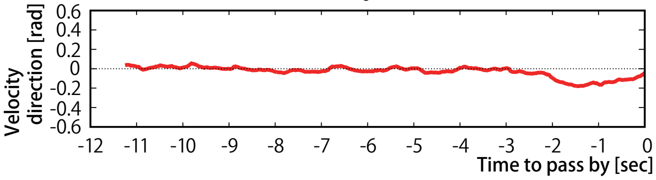
The authors quantitatively evaluated the difference in walking trajectories in different conditions. Figure 10(a) shows a typical passing by trajectory in the projection condition. The red line shows a trajectory of the pedestrian and blue shows a trajectory of the robotic wheelchair measured by the tracking system. The black dots represent the positions every one second. The trajectory is smooth and the black dots are at regular intervals, which indicates the pedestrian do not have to change the walking speed. Figure 10(b) shows the walking direction of the pedestrian until the time that they got the closest. It can be seen that the walking direction barely changed, resulting in smooth passing by interaction.

Figures 11 and 12 show a couple of examples without projection. These figures clearly show difference of pedestrian trajectories towards projection trajectories of Figure 10. In the case of Figure 11(a) the pedestrian walked slowly close to the wall just before the passing by. Figure 11(b) shows the change in the walking direction (zig-zag) a few seconds before they got close. Example of Figure 12 shows a case in which the pedestrian and the robotic wheelchair went to the same side. In this case the pedestrian stopped once, which sometimes occurs even in the case of humans when we fail to share our motion intentions properly. In the projection condition, such stopping behaviors were not observed by sharing the motion plan of the robotic wheelchair.

To evaluate the differences in the changes of the walking directions among the three conditions, the average of the variance of the walking directions were computed during the last four seconds before the closest distance they got. The averaged variance among the three conditions exhibited significant differences ($p < 0.05$, Wilcoxon signed-rank test, Benjamini-Hochberg-corrected)(Figure 13). The

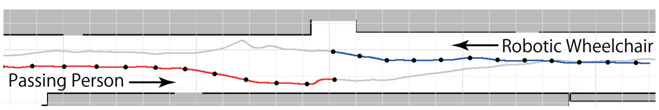


a) observed trajectories

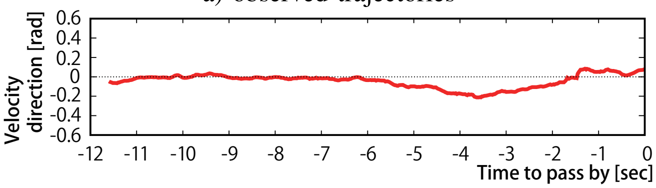


b) walking direction of the pedestrian

Fig. 10: Observed trajectories and a walking diretion in the projection condition. a) The path of the pedestrian is shown in red and the robotic wheelchair in blue. The black circles shows the position every one second. b) Walking direction of the pedestrian until they got closest.

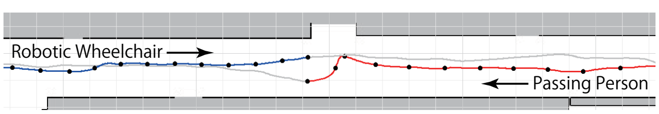


a) observed trajectories

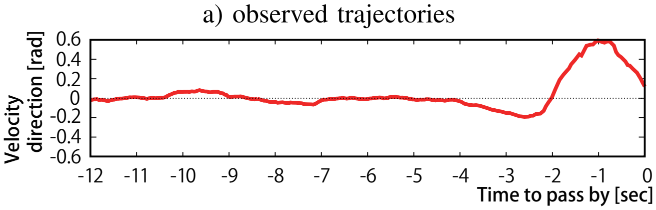


b) walking direction of the pedestrian

Fig. 11: Observed trajectories without projection.



a) observed trajectories



b) walking direction of the pedestrian

Fig. 12: Observed trajectories without projection. They went to the same side and the pedestrian once stopped.

averaged walking speed during the last three seconds was also computed and exhibited marginal significant difference ($p < 0.10$).

Changes in walking directions are clear when averaging the last four seconds and changes in walking speed are clear in the last three seconds. Results indicate that the pedestrian changed the walking direction when the distance to the wheelchair was closer than 10 m, followed by the decrease of the walking speed. In the projection condition, the change in the walking direction and decrease of the speed is clearly

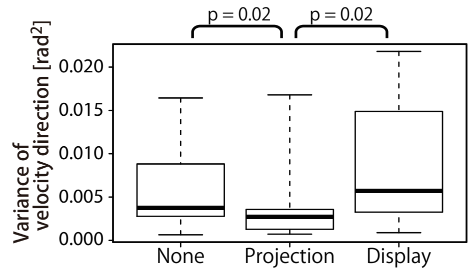


Fig. 13: Statistical analysis result of changes in variance of walking direction

smaller than other conditions. It is quantitatively shown that smoothness of human trajectory passing by the wheelchair improved with navigational intention communication.

VI. Discussion

The main purpose of the study was to point out the importance of intention communication in a passing by scenario where a light projection mapping proved to be a useful tool to simultaneously communicate information to the passenger and the out-group.

Light projection mapping approach to communicate robot navigational intentions was rated higher in all categories by the passenger and the pedestrian (Figures 8 and 9) showing statistical significance in both cases. From pedestrian perspective hand held display and no display were rated low; in both approaches the pedestrian did not received any extra information of the in-group movement.

In the case of the passenger hand-held display and light projection provided the same type of information, still, light projection was rated higher. A participant mentioned that "light projection on the environment gave him/her the insight in real world dimensions contrary to the hand held device". Passenger's feeling of empathy for the pedestrian could have had influence in higher scores in self comfort of light projection approach given that in some cultures like the Japanese, showing empathy or understanding for others in common spaces is common sense practice [26] [27]. Impression of comfortability and easiness to understand the movement of the passing person could be influenced by an anticipation form the empathy that the person could understand projected information and give way for the wheelchair.

This work presented an evaluation in a passing by scenario with an out-group formed by one person. It is left for future work the approach to pass by an out-group formed by multiple people. Evaluation of this work was based on questionnaires. In the case of the passenger, it is open for future work the evaluation with physiological measurements to monitor stress levels (physiological measurements on walking people are noisy).

Light projection mapping was used to show the future navigation path of the robotic wheelchair in a passing by scenario. This approach could be used together with the networked sensors to show passengers non-visible objects, i.e., people approaching in blind intersections or corners. It is also open for future work the evaluation under more complex and dynamic environments. In dynamic environments it would be necessary to show a combination between local (collision avoidance path) and global planned paths.

This work employed projection mapping as intention communication media which would require a powerful projector to be used outdoors. Implementation of navigational intention communication by using galvanic scanned laser pointer might be a possibility to extend this approach outdoors.

VII. Conclusions

This paper presented a navigational intention communication approach which communicates wheelchair's intentions to both passenger and people around them to perform comfortable navigation for both of them. The concept of intention communication was presented and implementation details of projection mapping wheelchair were shown. In this approach, the robotic wheelchair communicates its future trajectory as its intentions according to a goal intention by the passenger by light projection on the environment. Projected information also provides their joint intentions to the people around them.

The navigational intention communication system using projection mapping was evaluated through experiments with 16 participants. A comparison in an autonomous navigation task where the robotic wheelchair autonomously navigates the environment with and without intention communication was performed. Evaluation results significantly show human participant preference for having navigational intention communication for the wheelchair passenger and the person passing by it. Quantitative results show the motion of the person passing by the wheelchair with intention communication was significantly smoother compared to without intention communication.

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