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Communicating Directional Intent in Robot Navigation using Projection Indicators

Moondeep C. Shrestha, Tomoya Onishi, Ayano Kobayashi, Mitsuhiro Kamezaki, *Member*, *IEEE*, and Shigeki Sugano, *Fellow, IEEE*

***Abstract*— Smooth and efficient robot navigation among humans is a crucial requirement for successful integration of robots in human society. Towards this end, an indispensable characteristic of robot action is legibility while communicating its intention. However, unlike humans, present robots cannot convey its intention through human-like non-verbal communication. This paper explores the use of projection indicators for communicating directional intent of a robot across three different 'crossing scenarios' as a means of overcoming the shortcomings of the robot's non-verbal communication abilities. The results of the study show statistically significant improvement in perceived feelings of the measured attributes when using the auxiliary communication method. The studied method also improves cooperation from the participants. Nevertheless, the improvement in perceived feeling does not necessarily replicate in terms of smoothness across all the scenarios.**

I. Introduction

Autonomous navigation among humans remains a challenging task for current robots. Even with the recent advancements in sensing and actuation capabilities, state-of-the-art robots fall short in ensuring safe and efficient navigation performance. This is because autonomous navigation among humans requires a multitude of capabilities, which range from sensing, planning, and actuation, to social intelligence. When we consider humans, apart from highly evolved sensors and agile body, humans also possess the ability to understand and process social behavior and constraints. One key behavior that humans constantly make use of during navigation is two-way non-verbal communication [1] of directional intention. This communication allows easier prediction and pre-planning, resulting in a smooth navigation even in crowded situations. However, communicating and understanding directional intention relies on processing the combination of various components within kinesics [2], such as body posture, facial expressions, and eye movement. Current robotic platforms do not possess the capacity to exhibit human-like non-verbal communication and, cannot process and understand the non-verbal signals conveyed by humans. These inabilities make it difficult to generate a legible robot behavior. Hence, the resulting navigation interaction among humans and robots will be both uncomfortable and inefficient [3].

M. C. Shrestha, T. Onishi, and A. Kobayashi are with the Department of Modern Mechanical Engineering, School of Creative Science and Engineering, Waseda University, 17 Kikui-cho, Shinjuku-ku, Tokyo 162-0044, Japan (phone: +81-3-3203-4393; e-mail: moondeep73@aoni.waseda.jp).

M. Kamezaki is with the Research Institute for Science and Engineering(RISE), Waseda University, 17 Kikui-cho, Shinjuku-ku, Tokyo 162-0044, Japan (e-mail: kame-mitsu@aoni.waseda.jp). and JST PRESTO.

S. Sugano is with the Department of Modern Mechanical Engineering, School of Creative Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan (e-mail: sugano@waseda.jp). URL: http://www.sugano.mech.waseda.ac.jp/

Figure 1. Twendy-One [18] in a typical daily environment with people navigating around at different passing/crossing angles.

The importance of communicating intent for robot navigation becomes more apparent when we consider the drastic difference in dynamical abilities between humans and the state-of-the-art robots. At the comfortable and maximum walking speeds that range from 127.2 to 146.2 cm/s and 174.9 to 253.3 cm/s respectively [4], [5], humans can immediately react to sudden changes and correct any misjudgment of impending circumstances. Humans can easily perform evasive actions while maintaining balance, and they can virtually accelerate or stop instantaneously. These abilities allow them to navigate confidently even though they are uncertain of the future circumstances. Once again, owing to the limitations of the existing hardware and control designs, present robots are incapable of performing these sudden and flexible adjustments. These limitations further necessitate navigation behavior that produces fewer incidents of miscommunication and thereby, help robots to avoid situations where it must make sudden changes to their navigation commands.

As stated in the first paragraph, it is still difficult for the current robot technology to seamlessly communicate its intention with human-like behavior. One alternative method, however, can be the use of various auxiliary means of communication that are already prevalent in human society. Considering the necessity for and the likely benefits that can be realized with intent communication mechanisms, this study investigates the usage of one such auxiliary means (projection indication) to see whether it can effectively aid robot navigation. This paper focuses on the work of projection indication whereas the authors' previous works presented the results of shoulder-based light, and display signals [6], [7].

II. Related Work

There are studies that have shown that robots can convey directional intent by using whole-body motions [8], as well as gaze and head movements [9]. However, this paper specifi-

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cally focuses on explicit audiovisual communication as an alternative means to aid robotic navigation among humans. One key advantage that the audiovisual means have over the body and/or gaze movements is that they can elicit attention from nearby agents even when they are focusing on something else. There are plenty of studies that have analyzed the use and effects of explicit intent communication in human-robot interaction (HRI) field. However, these studies involve directly interacting agents whose interaction forms the core of the task. In comparison, robot navigation, excluding initiating conversation or handing over objects, consists of interaction that is a deviation or disturbance from the intended task. Consequently, only a few recent studies have analyzed the use and effects of explicit intent communication in human-robot navigation studies.

1) Auxiliary communication: For the specific focus of this paper, Matsumaru et al. have published a few papers during the mid-2000s. They have proposed various auxiliary communicating means for navigation, such as preliminary announcement and an indication to convey directional intention [10] – [12]. The proposed methods use lamps, blowout on a turntable, light ray, and projection [12]. Another approach that uses eyeball expression and makes a comparison between four different types of eyeball expressions is proposed in [13]. One common theme in the work of Matsumaru et al. is the focus on novel methods and building systems for the implementation of those methods. However, for the experiment design and analysis part, the authors have removed the HRI aspect since the participants never interact with the robot directly. Participants have always acted as a bystander and rated the different system by looking from a distance. Naturally, there will be great differences between a bystander experiences versus direct interaction while moving together with the robot.

2) Analysis of collaboration with robot: Most recent works include experiments where the participants move in collaboration with the robot and the efficacy of the systems are analyzed both subjectively and objectively. In [14], LED-based indicators are implemented in a quadcopter to test four different designs for intent communication. However, in this study, the participants analyze the different systems by sitting in front of a glass window. In [15], the authors have proposed two alternative approaches for conveying navigational intent. They have utilized 'implicit joint attention using gaze', and

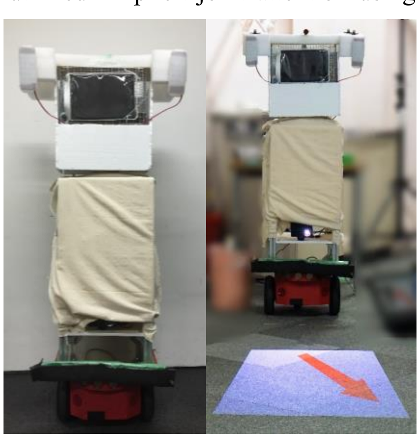


Figure 2. Robotic platform built on Pioneer 3-DX mobile base (left). Projection indication using arrow (right).

'turn indicators' by adopting the semantics of a car's turn indicators. Finally, they have used a control behavior and made a comparison between all of them.

3) Light projection system: Some studies analyzed light projection systems in their robotic platforms for communicating robot's future trajectories. The study in [16] implements a light projection system in an autonomously driven participant-equipped wheelchair that shows the future trajectory of the robotic system. The study design also includes a hand-held display for showing navigation intention and makes a comparison across both systems, as well as with a baseline without any indication. In [17], the authors propose the use of a LED projector to communicate the internal state for automatic guided vehicles. Their experiment design includes a 180 degrees' passing-by interaction between the participants and the robot, and the participants are instructed to veer off in the opposite direction after the robot changes its direction. As is typical in navigation studies, the above-mentioned studies limit their analysis to a straight passing-by scenario. However, as represented in Fig. 1, typical daily environment involves people interacting in a myriad of passing/crossing scenarios. Hence, it is essential to test the intent communication mechanisms across different crossing settings to analyze its true effectiveness. This paper investigates the usability of the communication modes in three different passing/crossing scenarios (90, 135, and 180 degrees). Even though these scenarios do not form an exhaustive list, they do present a simplified representation of every day possible interactions.

III. Directional Intent Communication System

A. Communication mechanism considerations

The daily environment consists of people walking around freely with their mind preoccupied in some or most cases. Under this situation, a rich design with plenty of information will be ineffective, as people may not have enough time to focus and concentrate. Any communication system (audiovisual system in this case) used for conveying directional intent should thus have a simple and highly intuitive design. Moreover, invasive methods are unacceptable barring emergencies. Systems that are already well integrated into human society will have a higher chance of being easily understood, and thus, readily accepted. These considerations and/or requirements have shaped the selection of communication modules for this and the author's previous study [6], [7].

Figure 2 shows the projection indicators used in this study. The projector used in the robot is Optoma ML750 [19]. For the direction convention, the direction of projected ray represents the robot's intended direction of travel. This decision was made because the arrow starts from the base and points outwards. The red color is chosen for the projected arrow because it attracts attention [20]. The different communication modes used in this paper are as follows. The following paragraphs explain the rationale behind the selection.

- No indication (NS);
- Projection (projected ray) without sound (PJ);
- Projection (projected ray) with sound (PJS).

The first mode is the NS which serves as the baseline. PJ mode is the core idea that is to be tested. The third and final indication method, PJS, employs the turning signal sound

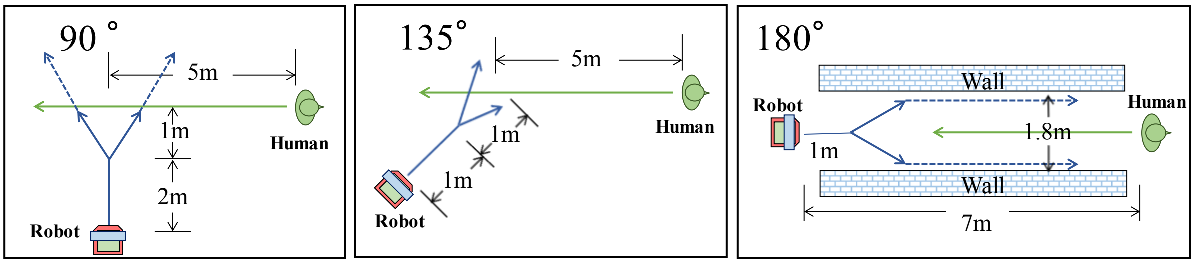


Figure 3. Layout of the experiment based on the scenarios of 90 degrees (left), 135 degrees (center) and 180 degrees (right).

from 1997 Pontiac Sunfire model car. The design choice of sound is in alignment with the philosophy explained in the first paragraph of this subsection. The public is familiar with the automobile's typical turning indication sound. Another thing to note with the use of sound is that it is not intended for conveying directional intent. The idea is to use sound to attract attention and in this study, the authors are simply trying to study the effects of having sound with other visual modules. Thus, the authors have not designed a mode which includes sound indication only. This series of preliminary investigation is focused on the effectiveness and versatility of the different explicit intent communication mechanisms. As such, the design selections are intentionally based on simplicity. Even though different variations in the size, shape, color, and other similar characteristics may result in an improved performance, such considerations require a separate study.

B. *Mobile robot platform and behavior*

Figure 2 shows the robotic platform used in the study. It is a lightweight platform built on top of Pioneer 3-DX mobile base. It measures 150 cm in height and 57 cm in width. For the robot's motion, a pre-planned behavior was implemented to maintain a standard behavior across any human variations. Sometimes, the robot autonomously adjusting to the human's variation can bias (positively or negatively) that trial. However, for safety considerations in the case where participants misjudged the robot's intention leading to an impending collision, the robot was programmed to autonomously slow down and stop. We also implemented an emergency stop button.

Figure 3 illustrates the path of the robot for all scenarios. The robot moves forward for 2 meters before turning at an angle of 30 degrees either side in the 90 degrees' scenario. For 135 degrees crossing, the robot turns right (15 degrees) or left (30 degrees) after following a straight 1-meter path. Finally, for 180 degrees passing, the robot turns either left or right after traversing straight for 1 m, and continues a straight path after changing its direction. The maximum speed of the robot was limited to 0.7 m/s owing to the hardware limitations and safety considerations for the participants. During the pilot study, speeds of 0.5 m/s and below were very slow, and any speeds equal to 1 m/s or more made the participants nervous and increased the risk of collisions.

IV. Study Design

This section explains the experimental design and the different measured variables used in the analysis presented in later sections. The authors recruited 16 participants (10 male and 6 female) for the three scenarios through flyers and word of mouth. The participants' age ranged from 19 to 38 (M = 26.6 and SD = 5.3), and they rated mean values of 5.4 and 5.9 (on a scale of 1 to 9) for the questionnaires of 'familiarity with robots' and 'prior interaction with robots', respectively. The participants were not informed about the details of the experiment except for the generic 'human-robot interaction experiment' explanation prior to the experiment. Once the participants arrived at the experiment location, they were briefed about the experimental task (explained below), and asked to sign a consent form and fill out a survey, before proceeding with the experiment.

A. *Experiment design*

The layouts of the experiment design are shown in Fig. 3. For the 180 degrees' scenario, the participants walked through an artificial corridor spanning 1.8 meters whereas, for the remaining scenarios, the participants' movements were not restricted by any structures. The participants' movements were restricted to control their navigation behavior so that they could not avoid the future interaction by detouring completely. However, for other scenarios, the existence of similar structure would impede vision and they were therefore not used.

The experiments were performed in two different sets (randomized for each participant) owing to the labor and time constraints (assembling and disassembling the wall structure). One set comprised of 180 degrees' scenario where the participants performed six randomized trials (2 x 3 modes) for the three different modes stated in Section III. 135 and 90 degrees' scenario experiments were conducted in another set with each scenario once again consisting of six randomized trials for the same three modes. Each participant participated in 18 trials altogether. After each trial, participants were asked to rate the navigation interaction based on four different metrics. At the end of each scenario, the participants answered a questionnaire (on a scale of 1 to 9) about the different modes and participated in an interview.

To ensure a meaningful narrative leading to a natural interaction, the participants were asked to perform a simple task as a part of the experiment. At each end of the participant's path, randomly numbered plastic boxes were placed on top of a small table. In addition to the plastic boxes, each table contained one cardboard shelf with appropriately numbered slots. For all the scenarios, and every trial, the participants were asked to randomly select three plastic boxes from the table into a small cardboard box, and after receiving the signal from the experimenter, carry the cardboard box to the other end of the table. At the other end, they were asked to enter the plastic boxes into appropriate slots in the shelf. As Fig. 3 shows, the experiment always started with the participants facing in the

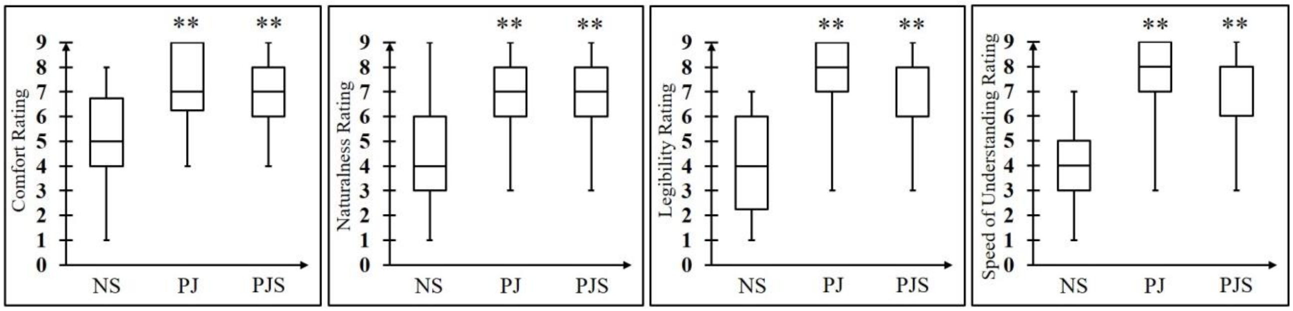


Figure 4. Subjective results for the four-different metrics across the 180 degrees passing scenario. The asterisk on top of the bar represents the significance against the baseline. (**p < 0.001).

opposite direction. The participants were asked to turn around and move forward simultaneously, after receiving a signal from the experimenter. The robot's movement and the indication were initiated along with the signal. This experiment design ensured an initial momentum for the participants prompting them to face the signal and react as soon as possible.

B. *Measured variables*

The participants' trajectories were recorded using the Optitrack Prime 13 motion capture system [21] during the experiment. Based on the trajectory data, two quantitative measures (cooperation rate, and hesitation occurrence) were calculated and analyzed. Cooperation refers to a participant's compliance to the robot's request. In daily environments, people cooperate with each other to achieve a smooth navigation interaction [22]. This measure evaluates how instinctively the different methods can persuade early cooperation so that the robot can avoid future situations where it must stop or evade suddenly. The cooperation action is determined by analyzing participants' deviating points for each trial. A successful cooperation action is defined as a situation in which the participant (a) correctly understands the signal and (b) deviates according within 1 second. For hesitation occurrence, the concept of hesitation signal from [23] is utilized, which presents an idea of hesitation signals based on sudden velocity changes that are atypical to a smooth interaction. Any time a participant slows down, accelerates or comes to a momentary halt, hesitation is registered. For this paper, hesitation occurrence is calculated by analyzing the velocity profile of the trajectory data, and later confirming it manually though the videos. Any change of $\Delta v \geq 0.4$ m/s in the filtered trajectory data after the initial acceleration is manually confirmed as an occurrence of hesitation.

For qualitative data, custom-based questionnaires were administered after each trial, and interviews were conducted after each scenario. The questionnaire included four different measures of 'comfort', 'naturalness', 'legibility', and 'speed of understanding'. The first three measures were adopted based on the classification of 'human-aware navigation' studies presented in [24]. The study in [24] presents a thorough explanation of what these three parameters signify in the scope of human-centered navigation. The final measure, 'speed of understanding' analyzes how quickly were the participants able to understand the robot's directional intention. Finally, FHD videos of all the trials were also captured.

V. RESULTS

A. *Subjective results*

As explained in the previous section, the participants rated the different modes of communication in terms of four different metrics. Figures 4, 5, and 6 present the graphical representation of all the metrics across all three scenarios. A one-way repeated - measures ANOVA was performed (after testing for normality for each group) based on the three different modes and post-hoc comparisons were done using Tukey's Honestly Significant Difference (HSD) for each measure. The following paragraphs will explain the statistical results for each scenario.

Figure 4 shows the results of the 180 degrees' scenario custom-based Likert scale questions for the four metrics. As can be seen from the graph, participants have significantly rated all the four measures in favor of projection-based indication (with or without sound). The double asterisk in the box-and-whisker plots represents a significance of $p < 0.001$. Participants consistently found the navigation interaction with projection indication to be comfortable and natural. Further, with the projection indication, the robot's navigation behavior was considered legible which resulted in a faster understanding of the robot's intention. As Figs. 5 and 6 shows, similar results hold true for the case of 135 and 90 degrees' scenarios.

There are no significant differences in the perceived ratings of robot's navigation behavior by having the added factor of sound. Participants rated both the PJ and PJS mechanisms to be equally comfortable and natural across all the scenarios.

B. *Observed human trajectory analysis*

Figure 7 (a) shows the cooperation percentage for the three different intent communication mechanisms for 180 degrees' passing. As can be seen from the figure, both the PJ and PJS significantly increases cooperation among the participants when compared to the baseline. Figures 7 (b–d) present the percentages of hesitation occurrence for the three modes across all scenarios. In the case of 180 degrees, using the projection indication (with or with sound) resulted in a much lower number of hesitation occurrence. However, as the angle becomes steeper, the differences of hesitation occurrence between having indication or not starts decreasing. For 90 degrees' scenario, the differences in hesitation occurrence between the projection indication and the baseline is very low. Nevertheless, use of the projection indication reduced the occurrence of hesitation across all scenarios.

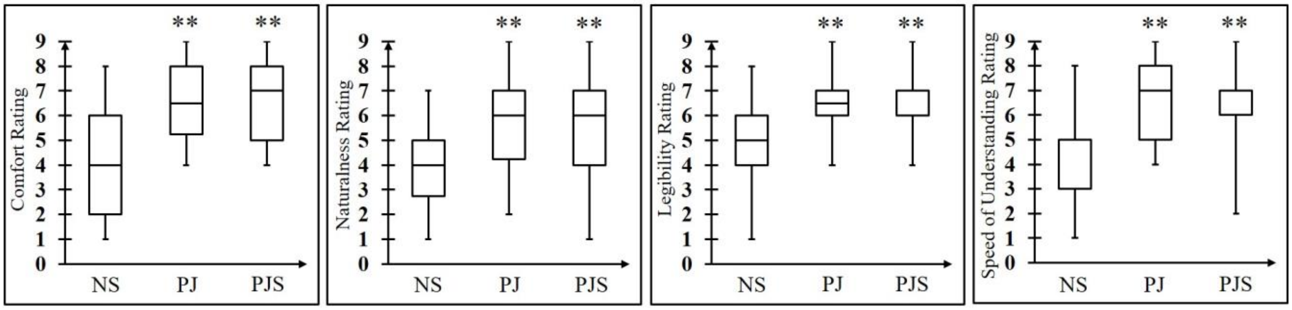


Figure 5. Subjective results for the four-different metrics across the 135 degrees passing scenario. The asterisk on top of the bar represents the significance against the baseline. (**p < 0.001).

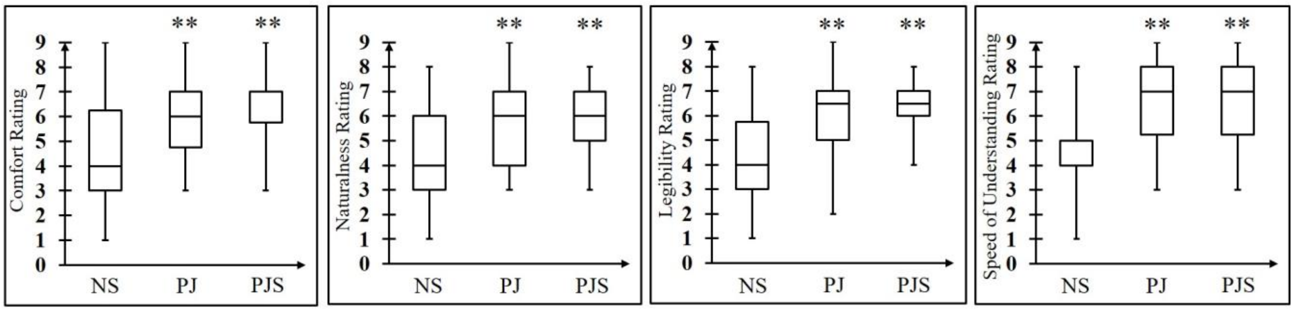
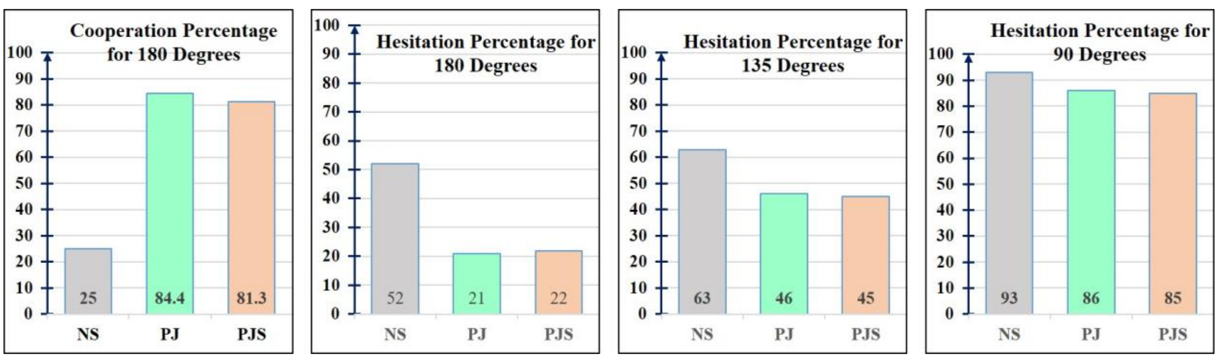


Figure 6. Subjective results for the four-different metrics across the 90 degrees passing scenario. The asterisk on top of the bar represents the significance against the baseline. (**p < 0.001).



(a) (b) (c) (d)

Figure 7. Cooperation percentage for 180 degrees (a), and Hesitation percentage for 180, 135, and 90 degrees' scenarios respectively (b, c, and d respectively).

Finally, Figs. 8 and 9 present typical trajectories of participants when having no indication versus projection indication, respectively during 180 degrees passing. In the case of Fig. 9, most participants continued in a straight line and only changed their directions later. However, when using the projection indication, participants could easily cooperate to the robot's request, and therefore they promptly selected a suitable path.

VI. Discussion

The main purpose of this study was to test the versatility and effectiveness of the projected light-based directional intent communication system for human-centered navigation.

The perceived ratings show that the projection indication is versatile when it comes to different interaction angles. However, the quantitative measures paint a slightly different picture, especially for 90 degrees' scenario. This discrepancy could be due to the inherent limits of humans wherein, humans cannot visualize moving objects perfectly. For instance, participants understood the robot's intention in 90 degrees' scenario. However, they could not exactly visualize where they would cross the robot in the exact future. This could have led to an improved perceived feeling but a non-smooth trajectory.

Many participants rated the projection indication to be user-friendly and intuitive. The comments during the interview are also in alignment with the perceived ratings. Few examples include, "I can roughly tell which direction the robot is going, so that I can avoid it"; "The projected arrow looks interesting, and it makes me feel this is something as robots or other technology."; "very intuitive". As also found in the authors' previous study, participants sometimes found sound to be disturbing even though it did not affect their perceived feelings or trajectory regarding the overall navigation experience.

Since the research served as a preliminary investigation, the design parameters were constructed in a simple style. There were many parameters that could be varied during the design stage. However, since the motivation behind the study was to test the effectiveness and versatility of the concerned mechanism, the authors did not attempt to investigate the variations

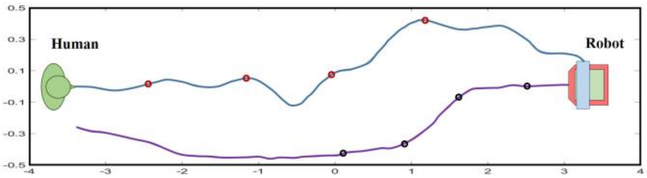


Figure 8. Typical observed trajectory for NS in 180 degrees' scenario with the participant and robot in the starting position. The red (Human) and black (Robot) circles represents the positions after t = 1, 2, 3, and 4 seconds.

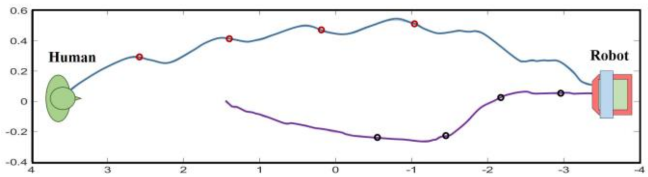


Figure 9. Typical observed trajectory for PS in 180 degrees' scenario with the participant and robot in the starting position. The red (Human) and black (Robot) circles represents the positions after t = 1, 2, 3, and 4 seconds.

within the size, shape and colors of the indication mechanism. Nevertheless, it will be interesting to see whether different variations can improve the results further.

Finally, limitations of this experiment design must be acknowledged. First, the perceived feelings in any study can be influenced by the physical appearance and traits of the robot. It will be interesting to see whether the results will differ in case of other mobile robots with different designs. Second, the participants are mostly young male Japanese.

VII. Conclusion

This paper explored the usage of an explicit visual directional intent communication system in the context of human-centered mobile robotics. The specific approach in this paper consists of projection (projected light ray) directional intent communication system. The projection system is tested across three different navigation scenarios that represent a simplified summarization of possible everyday encounters, and then compared against a control behavior to test its efficacy and versatility. The efficacy and versatility qualities are analyzed through qualitative and quantitative measures. The results indicate that the participants perceive the projected light ray to have a positive impact across all scenarios, with the perceived ratings of the projected light ray getting relatively better (against the control behavior) as the angle of interaction becomes acuter. Finally, the results of the observed trajectories show that even though the perceived measures improve with the use of the projected light-based mechanism, it does not effectively improve navigation smoothness, except for in the case of 180 degrees passing.

Future work includes improvement of the interface-aspect of both the projection and shoulder lights-based mechanisms, with further experiments in more complex scenarios involving multiple people. The projection and shoulder lights signaling mechanisms will then be incorporated in the wheel-based humanoid robot [18] to produce a navigation framework that is aided by the idea of conveying the robot's future intent.

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