Lessons learned from user experiments with a socially-aware mobile robot

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***Abstract*— Mobile robots need to understand human actions and produce socially accepted behaviors. In this paper, we address this issue and propose a method for mobile robots to communicate their intentions to humans. We present a retrofitted MiR100 equipped with an RGB-D camera and a projector. The RGB-D camera is used in human-aware navigation to recognize humans and predict their trajectories for the robot to proactively react to human actions, creating a safe and seamless human-robot collaboration. The projector acts a human-robot communication channel to transmit the robot's motion intentions. To evaluate the system, we performed extensive human-centered HRI experiments where 30 participants interacted with the mobile robot. Our experiments demonstrated that the social acceptance of the mobile robot was favoured by the human-aware navigation, and its combination with the projector raised the mobile robot's usability and comfort by 6% and 12%, respectively.**

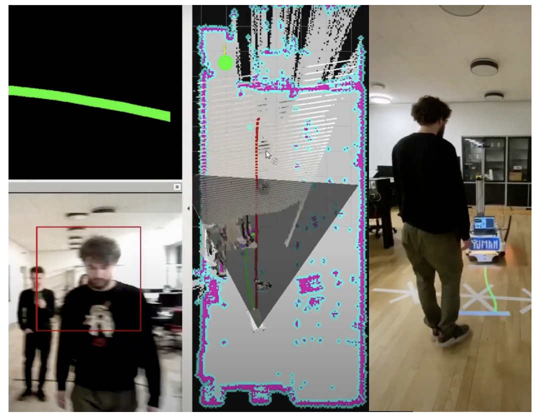

Fig. 1. (Top left) planned local trajectory, (bottom left) human detection based on the on-board camera, (middle) map of the environment, (right) mobile robot navigating in a classroom exhibiting a socially-aware behavior.

I. Introduction

Mobile robots have proven successful in constrained industrial environments [1], [2]. The challenge arises when introducing robots to social settings such as shopping centres, classrooms, hospitals or nursing homes. In such challenging environments, industrial mobile robots present certain limitations. Therefore, many researchers have enhanced their robots with human-aware navigation features [3]–[5] and even adapted them to follow social awareness protocols during the COVID-19 pandemic [6]–[8].

Transparent communication in human-robot interaction (HRI) is proven to assist with predicting the robot's behavior and increase the trust humans have towards robots [9], [10].

Examples in recent literature combine various cameras, projectors and AR technologies with mobile robots to achieve transparent communication and socially acceptable robot behavior [11]–[14]. Despite the plethora of such systems, there is still a gap of knowledge concerning the systems' usability. It remains unclear which modules provide the most usable mobile platform for human-aware navigation and transparent robot-human communication. Moreover, most surveys used to track user impressions for these systems, lack standardised metrics and keep their questions hidden rendering their replication almost impossible.

In this paper, we bridge these two gaps by performing a comprehensive usability study of our proposed robot and by sharing the backend of our questionnaires to enable easier reproducibility from future studies. We equipped a MiR100 mobile robot with an RGB-D camera and a projector and performed human-aware navigation, as shown in Fig. 1. We evaluated the user experience, social acceptance and usability of the robot by conducting experiments with 30 participants based on the standardised USUS [15] and UTAUT [16] metrics. Our experiments confirmed a projector is an excellent tool for transparent communication in HRI as it significantly improves robot's usability and user experience.

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II. Related Work

Studies have shown that humans can communicate effectively with non-verbal signals [17], [18]. We can rely on our social cognition to infer information based on our knowledge of the social world, to interpret others, and proactively predict their intentions. When it comes to collaboration between humans and robots, non-verbal communication can also be used for robust prediction of the robot's intentions [19], [20].

One of the most effective ways to communicate those intentions is augmented reality (AR) and light signals. Chadalavada et al. [21] used a fork-lift robot equipped with a video projector to project a simplified map with the robot's plan. The experiments show an increase in user ratings compared to when the robot navigated without conveying its intentions. Overall, the robot was more communicative, predictable, and transparent than without a projection system.

In the same direction, Coovert et al. [22] projects an arrow on the floor indicating the robot's directions and evaluates its ability to transmit its intentions by asking humans to predict the robot's action. The results were favourable, and humans could predict these actions in most cases. As an alternative, Palinko et al. [23] used the robot platform's lights to signal various robot's behaviors while manually controlling the robot using a joystick. Different light signalling methods were used, such as blinking lights—an analogy to the standard car turn signalling—and rotating lights.

Based on the presented techniques, it is clear that transmitting the robot movement intentions has the potential for more transparent robot-human communication. Approaches such as Palinko et al. [23] do not provide conclusive realistic results due to the usage of a joystick to control the robot. In a real scenario, the robot needs to navigate autonomously, resulting in arbitrary and sporadic trajectories, much different from those produced by a human-operated robot.

Moreover, to provide realistic HRI, it is necessary to evaluate the usability and acceptance of the chosen communication method. The above mentioned approaches use custom evaluation frameworks. It is therefore challenging to compare and judge which method is most useful to humans. However, multiple studies have shown that evaluation methods for HRI can be standardised and reused [24]. In our experiments, we used the so-called USUS Evaluation Framework for HRI proposed by Weiss et al. [15], which evaluates the factors of usability, social acceptance, user experience, and societal impact. This framework aims at understanding to what degree HRI methods contribute to humans accepting robots as part of society. To further measure social acceptance, we used the Unified theory of acceptance and use of technology (UTAUT) [25], adapted from Han et al. [16] to evaluate the acceptability towards an educational tele-presence robot.

III. System Description

We study HRI applied to a mobile base, depicted in Fig. 2, considering a robust human-aware navigation stack and a projection system to transmit the robot movement intentions.

A. Human-aware Navigation

We consider the navigation in a known environment. Inspired by how humans navigate by understanding each other's behaviors and respecting personal space, we approached navigation as a cooperative activity between robots and humans. We used the RGB-D camera to capture a more realistic and accurate representation of the environment.

We utilize a people tracking module to predict their trajectories. Based on this information, we establish the necessary proxemics to proactively plan the robot's trajectory. Demonstrations of more experiments can be found here: `https://youtu.be/gJCiKonCv9A`

B. Robot-Human Communication

To communicate the robot motion intentions, we project the robot's planned trajectory as a line on the floor, showing its local plan. Since the users have no other way to perceive if the robot acknowledge their presence, they rely to the projected trajectory to rate the robot's communication abilities and gain trust in its human-aware navigation capabilities. The implementation was inspired from Han et al. [26]

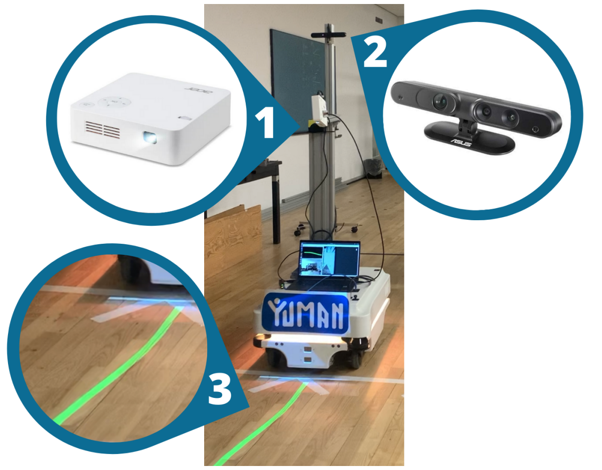


Fig. 2. MiR100 mobile robot used in our HRI experiments. We added an Asus Xtion Pro Live RGBD camera(1) and an Acer C202i projector(2). The projected image illustrates the robot's navigation plan(3).

IV. Usability Study

A. Study Design

30 people, divided in 10 groups of 3 people each, participated in the usability study. Two experiments were conducted in a 8×15 m room. Each experiment involved 5 groups (15 people), and no individual participated in both experiments. Both experiments 1 and 2 consisted 2 sub-experiments (dubbed respectively, experiments 1.1, 1.2, 2.1 and 2.2).

a) Experiment 1: In experiment 1.1, the robot autonomously navigated around the classroom in a social manner without projecting its intentions (Projector OFF) while the participants had to walk along the classroom interacting with the robot as much as desired. In experiment 1.2 was carried out in the same way as above, with the modification that a projector was used (Projector ON) to project a line with the robot's trajectory plan onto the classroom floor.

We observed that after a few initial runs, the first participants were comfortable with the robot without the projector.

b) Experiment 2: To measure if the projector affects the initial trust participants exhibited towards the robot and the overall social acceptance, in experiment 2, we modified the order in which participants encountered the robot and the communication system. In experiment 2.1, the robot autonomously navigated projecting its intentions (Projector ON), and in experiment 2.2, in the same setting the robot was not projecting its intentions (Projector OFF).

B. User Input

Participant filled in a survey, organized around the USUS and UTAUT frameworks, to explicitly evaluate their experience with the robot. The following areas were covered:

a) Usability: We evaluated the robot usability with and without the projector based on the System Usability Scale (SUS), an industry standard for measuring the usability of technological systems. This is represented as ten-items with a five-point Likert scale (from strongly disagree to strongly agree). The scores are converted to a 0-100 scale, where a system with a SUS score above 68 is considered sufficiently usable. Some of the questions used in both cases are:

1) *I think I would like to interact with this mobile robot frequently.*
2) *I found the mobile robot's movement unnecessarily complex.*
3) *I thought the mobile robot's movement was easy to comprehend.*
4) *I think that I would need the support of a technical person to be able to interact with this mobile robot.*
5) *I trusted the mobile robot actions when the projector was ON/OFF.*

b) Social Acceptance: Social acceptance was evaluated using the UTAUT framework, inspired by Han et al. [16]. We used four questions with a five-point scale and measured four factors: Performance Expectancy (1), Effort Expectancy (2), Attitude towards Using Technology (3) and Self Efficacy (4).

1) *The behavior of this mobile robot is as I expected it.*
2) *How much effort does it require from you to understand where the robot is going to go?*
3) *I think the usage of a projector was good indicator of the robot's movement goals.*
4) *If I were to encounter the robot alone, I would be afraid.*

To quantify the social acceptance factor we have chosen a scoring similar to SUS. Each question contributes equally to the SUS score, negative questions (2, 4) are inverted, and the raw SUS score is normalized to match the 0-100 scale.

c) User Experience: To evaluate the user experience, we measured how engaging (1) and interesting (2) the robot seemed to the participants:

1) *Who would you choose to deliver the coffee for you?*
   1. The Robot, 2. A Human.
2) *Would the robot seem interesting to use?*
   1. Extremely, 2. A bit, 3. Not much, 4. Not at all.

The score was normalized to match the 0-100 scale.

d) Personalised Affirmations: We asked seven personalised affirmations with a five-point Likert scale to evaluate: (1-3) the *comfort* of the participants with the robot at the start and end of the experiment; (4-5) the *perceived competence* describing the belief that the participants were able to interact with the robot; (6-7) the *performance expectancy* to which the robot could improve the participants daily activities.

1) *When the projector was turned OFF, I was comfortable approaching the robot.*
2) *After the projector was turned ON, I was comfortable approaching the robot.*
3) *If encountering the robot alone, I would walk more safely if the projector is ON.*
4) *It was easy to move along the robot.*
5) *It was easy to understand the usage of the projector.*
6) *I believe that the use of the robot for transporting stuff would improve my study life.*
7) *I used the projector to see where the robot was going.*

To quantify the results, we compute the average score for each group of questions and assign it to its respective factor.

V. Evaluation

Out of 30 participants, 56.7% were male, and the prominent age group was between 20 and 25 years old; 66% of the participants have a background in Robotics or Electrical Engineering, the remaining were engineers outside the robotics field. They all interacted with robots before, specifically with robot vacuums and classroom robots. However, 33% of the participants never programmed and/or worked with robots.

a) Usability: The usability score differs based on the order in which participants encountered the mobile robot. The 5 groups in experiments 1.1 and 1.2 rated usability with a SUS score of 77.5, whereas experiments 2.1 and 2.2 have a SUS score of 85 and 80, respectively.

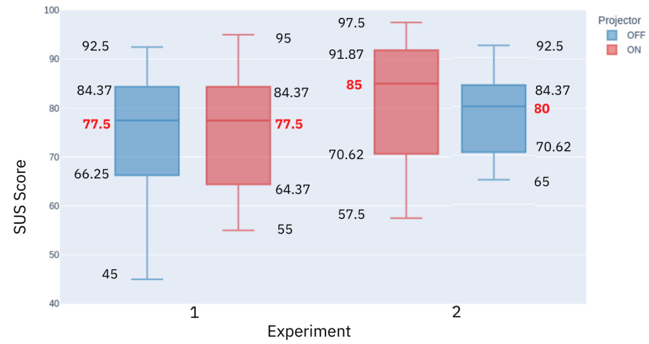


Fig. 3. SUS score box plots. Experiment 1 has an average SUS score of 77.5 and experiment 2 has an average SUS score of 82.5.

Examining the results presented in Fig. 3, it can be seen that participants in experiment 1 did not experience a meaningful change in the robot's usability after turning ON the projector. On the contrary, in experiment 2 the robot was considered to be more usable when the projector was ON.

In experiment 1.1, the robot had a high usability score when the projector was OFF, and the introduction of the projector did not have an apparent effect on the usability factor. However, in experiment 2.1, participants used the projected objects to interpret the robot's motion. As this was their first interaction with the robot, in experiment 2.2, the absence of the motion indicator became more noticeable, resulting in a decrease in the robot's usability.

b) Social Acceptance: The resulting median social acceptance scores for experiment 1 and 2 are 87.5 and 81.5, depicted in Fig. 4. Hence, the order in which participants encounter the robot (projector ON or OFF) slightly affects the social acceptance. Participants in experiment 1 had their last interaction with the robot with the projector ON, which enhances their experience, as it will be concluded with the user experience results. Overall, the average social acceptance for both experiments is 84.375, indicating a high social acceptance towards the robot with the projector.

The standard UTAUT model comprises 7 indicators. To validate if the 4 selected factors can reliably be used to measure the social acceptance of the robot, the Cronbach's Alpha score was computed. The obtained results showed that the modified UTAUT model for a mobile robot with a projector has a Cronbach Alpha of 0.71, considered acceptable [27].

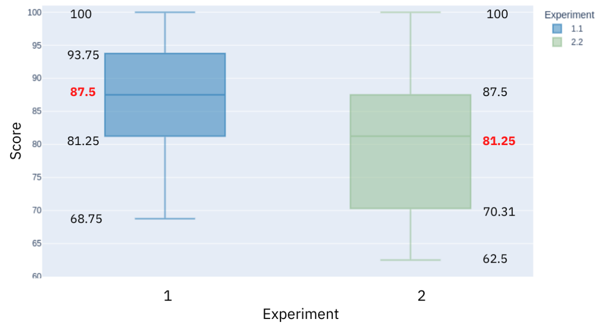


Fig. 4. Box Plot of Social Acceptance rating evaluation scores. The average scores are 82.5 in experiment 1 and 81.6 in experiment 2.

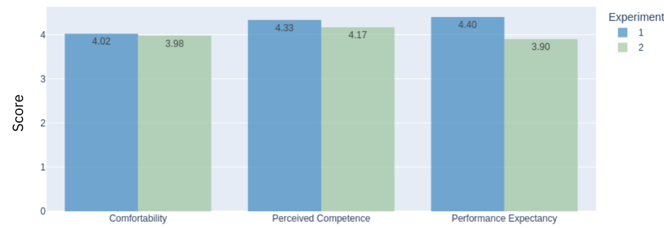
c) User Experience: The engagement factor results reveal that 73.3% participants prefer the robot to a human in experiment 1 and 60% in experiment 2. In this case, the participants in experiment 1, who interacted with the robot and the projector at the end of the experiment, were more eager to engage with the robot. However, this question raised ambiguity, as some participants were more concerned about the details in which the coffee is received rather than the interaction itself. 93.3% of participants agree that the robot is enjoyable to use in experiment 1, and 86.7% in experiment 2. Some participants highlighted that the robot seemed to be alive during the experiments. Hence, the robot received a positive user experience review and very high interest.

d) Personalised Affirmations: The use of the mobile robot with the projector received consistently high scores from each participant in every measured factor, as illustrated in Fig. 5a. The slight score difference between experiments indicates that the order participants interacted with the robot did not affect the perceived comfort and competence factors.

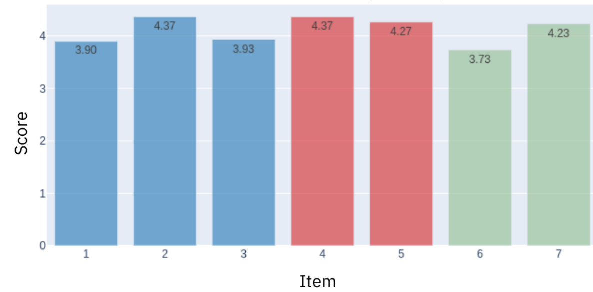
To better understand the influence the projector had on the participants' *Comfortability*, *Perceived Competence* and *Performance Expectancy*, we individually examined the average scores for the seven items. The results are presented in Fig. 5b. The comfortability with the robot is rated at 3.9 when the projector is OFF (Item 1) and 4.37 when the projector is ON (Item 2). Consequently, we can claim that using a projector as a communication system for the robot intentions enhances the comfortability of humans towards the robot.

VI. Discussion and Future Work

This paper presents a system for human-aware navigation and human-robot communication using a projector with the goal of testing if such system increases robot's usability, social acceptance and user experience. Our experiments and surveys using the USUS and UTAUT frameworks demonstrated that introducing a projector as communication channel, increases robot usability, social acceptance and the feeling of comfort. The overall high scores indicate that using human-aware navigation was crucial for participants to feel safe and easily trust the robot. After the first interactions with the robot, the participants realized that the robot could recognize and avoid them keeping safe distances. Hence, they



(a) Average Score Histogram of Personalised Affirmations factors in experiment 1 and 2. The overall score is 4.1 (out of 5).



(b) Personalised Affirmations items average score: Comfortability (1-3), Perceived Competence (4-5), and Performance Expectancy (6-7).

Fig. 5. Histograms of the Personalised Affirmations factors: Comfortability,Perceived Competence, and Performance Expectancy.

automatically felt safer and more comfortable. Therefore, the projector was an enhancement to human-aware navigation.

Dividing the experiments into two groups and alternating the order in which participants encountered the robot and the communication system revealed that after getting familiar with the robot without the projector, the participants did not experience a significant change in their experience. However, in the opposite setting, participants noticed the projector's absence after it was turned OFF and felt as if they could no longer understand where the robot was going. This fact is represented by the lower social acceptance scores in experiment 2, in contrast to the scores in experiment 1.

Therefore, it can be concluded that using a projector as a communication channel for a mobile base is a balanced manner for humans to understand the intentions of mobile robots and can be used to increase the feeling of comfort, usability, and social acceptance of robots in their initial interactions with humans. More specifically, there is a 6% increase in the robot's usability and a 12% increase in human acceptance towards the robot.

References

[1] R. E. Andersen, E. B. Hansen, D. Cerny, S. Madsen, B. Pulendralingam, S. Bøgh, and D. Chrysostomou, "Integration of a skill-based collaborative mobile robot in a smart cyber-physical environment," *Procedia Manufacturing*, vol. 11, pp. 114–123, 2017.

[2] V. Krueger, A. Chazoule, M. Crosby, A. Lasnier, M. R. Pedersen, F. Rovida, L. Nalpantidis, R. Petrick, C. Toscano, and G. Veiga, "A vertical and cyber-physical integration of cognitive robots in manufacturing," *Proceedings of the IEEE*, vol. 104, no. 5, pp. 1114–1127, 2016.

[3] T. Kruse, A. K. Pandey, R. Alami, and A. Kirsch, "Human-aware robot navigation: A survey," *Robotics and Autonomous Systems*, vol. 61, no. 12, pp. 1726–1743, 2013.

[4] J. Rios-Martinez, A. Spalanzani, and C. Laugier, "From proxemics theory to socially-aware navigation: A survey," *International Journal of Social Robotics*, vol. 7, no. 2, pp. 137–153, 2015.

[5] R. Möller, A. Furnari, S. Battiato, A. Härmä, and G. M. Farinella, "A survey on human-aware robot navigation," *Robotics and Autonomous Systems*, vol. 145, p. 103837, 2021.

[6] M. Cardona, F. Cortez, A. Palacios, and K. Cerros, "Mobile robots application against covid-19 pandemic," in *2020 IEEE ANDESCON*. IEEE, 2020, pp. 1–5.

[7] H. B. Barua, P. Pramanick, C. Sarkar, and T. H. Mg, "Let me join you! real-time f-formation recognition by a socially aware robot," in *2020 29th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 2020, pp. 371–377.

[8] R. Salek Shahrezaie, S. B. Banisetty, M. Mohammadi, and D. Feil-Seifer, "Towards deep reasoning on social rules for socially aware navigation," in *Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction*, 2021, pp. 515–518.

[9] P. A. Hancock, D. R. Billings, K. E. Schaefer, J. Y. Chen, E. J. De Visser, and R. Parasuraman, "A meta-analysis of factors affecting trust in human-robot interaction," *Human factors*, vol. 53, no. 5, pp. 517–527, 2011.

[10] M. Lewis, K. Sycara, and P. Walker, "The role of trust in human-robot interaction," in *Foundations of trusted autonomy*. Springer, Cham, 2018, pp. 135–159.

[11] A. Watanabe, T. Ikeda, Y. Morales, K. Shinozawa, T. Miyashita, and N. Hagita, "Communicating robotic navigational intentions," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2015, pp. 5763–5769.

[12] R. S. Andersen, O. Madsen, T. B. Moeslund, and H. B. Amor, "Projecting robot intentions into human environments," in *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 2016, pp. 294–301.

[13] B. Lewandowski, T. Wengefeld, S. Müller, M. Jenny, S. Glende, C. Schröter, A. Bley, and H.-M. Gross, "Socially compliant human-robot interaction for autonomous scanning tasks in supermarket environments," in *2020 29th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 2020, pp. 363–370.

[14] N. J. Hetherington, E. A. Croft, and H. M. Van der Loos, "Hey robot, which way are you going? nonverbal motion legibility cues for human-robot spatial interaction," *IEEE Robotics and Automation Letters*, vol. 6, no. 3, pp. 5010–5015, 2021.

[15] A. Weiss, R. Bernhaupt, M. Lankes, and M. Tscheligi, "The USUS evaluation framework for human-robot interaction," in *23rd Convention of the Society for the Study of Artificial Intelligence and Simulation of Behaviour, AISB 2009*, 2009, pp. 158–165.

[16] J. Han and D. Conti, "The use of UTAUT and post acceptance models to investigate the attitude towards a telepresence robot in an educational setting," *Robotics*, vol. 9, no. 2, p. 34, 2020.

[17] S.-J. Blakemore and J. Decety, "From the perception of action to the understanding of intention," *Nature Reviews Neuroscience*, vol. 2, no. 8, pp. 561–567, 2001.

[18] R. Buck and C. A. VanLear, "Verbal and nonverbal communication: Distinguishing symbolic, spontaneous, and pseudo-spontaneous nonverbal behavior," *Journal of communication*, vol. 52, no. 3, pp. 522–541, 2002.

[19] P. F. Dominey and F. Warneken, "The basis of shared intentions in human and robot cognition," vol. 29, no. 3. Elsevier, 2011, pp. 260–274.

[20] Z. Gong and Y. Zhang, "Robot signaling its intentions in human-robot teaming," in *HRI Workshop on Explainable Robotic Systems*, 2018.

[21] R. T. Chadalavada, H. Andreasson, R. Krug, and A. J. Lilienthal, "That's on my mind! robot to human intention communication through on-board projection on shared floor space," in *2015 European Conference on Mobile Robots (ECMR)*. IEEE, 2015, pp. 1–6.

[22] M. D. Coovert, T. Lee, I. Shindev, and Y. Sun, "Spatial augmented reality as a method for a mobile robot to communicate intended movement," *Computers in Human Behavior*, vol. 34, pp. 241–248, 2014.

[23] O. Palinko, E. R. Ramírez, W. K. Juel, N. Krüger, and L. Bodenhagen, "Intention indication for human aware robot navigation." in *VISIGRAPP (2: HUCAPP)*, 2020, pp. 64–74.

[24] C. Jost, B. Le Pévédic, T. Belpaeme, C. Bethel, D. Chrysostomou, N. Crook, M. Grandgeorge, and N. Mirnig, *Human-Robot Interaction: Evaluation Methods and Their Standardization*. Springer, 2020.

[25] V. Venkatesh, M. G. Morris, G. B. Davis, and F. D. Davis, "User acceptance of information technology: toward a unified view," *Institutions & Transition Economics: Microeconomic Issues eJournal*, vol. 27, no. 3, pp. 425–478, 2003.

[26] Z. Han, A. Wilkinson, J. Parrillo, J. Allspaw, and H. A. Yanco, "Projection mapping implementation: Enabling direct externalization of perception results and action intent to improve robot explainability," 2020. [Online]. Available: https://arxiv.org/abs/2010.02263

[27] S. S. Saidi and N. M. Siew, "Investigating the validity and reliability of survey attitude towards statistics instrument among rural secondary school students." *International Journal of Educational Methodology*, vol. 5, no. 4, pp. 651–661, 2019.