That's on my Mind! Robot to Human Intention Communication through on-board Projection on Shared Floor Space

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***Abstract*—The upcoming new generation of autonomous vehicles for transporting materials in industrial environments will be more versatile, flexible and efficient than traditional AGVs, which simply follow pre-defined paths. However, freely navigating vehicles can appear unpredictable to human workers and thus cause stress and render joint use of the available space inefficient. Here we address this issue and propose on-board intention projection on the shared floor space for communication from robot to human. We present a research prototype of a robotic fork-lift equipped with a LED projector to visualize internal state information and intents. We describe the projector system and discuss calibration issues. The robot's ability to communicate its intentions is evaluated in realistic situations where test subjects meet the robotic forklift. The results show that already adding simple information, such as the trajectory and the space to be occupied by the robot in the near future, is able to effectively improve human response to the robot.**

I. INTRODUCTION

This work focuses on improving the synergy between mobile robots and humans in shared work environments. This is achieved by enhancing the communication abilities of the robot which, in this paper, is the Automatic Guided Vehicle (AGV) shown in Fig. 1. Targeted work environments include warehouses.

AGV's have been providing transportation capabilities in intra-logistic applications for several decades. The most common navigation strategy is based on a pre-defined path. This imposes many limitations on the type of tasks the AGV can perform, as well as the behavior of the vehicle, *e.g.*, to perform obstacle avoidance. However, due to the limited motions allowed, pre-defining paths make it easy for workers to be able to predict the motion of the vehicle since the paths will typically be (indirectly) marked on the floor after some time of operation due to the wear of tires which leaves a trail. Commonly, AGV's are also equipped with blinkers to indicate turning directions.

The next generation of autonomous vehicles for transporting materials will not simply follow predefined paths, but allow for more flexibility to better utilize the resources and to provide more services such as loading and unloading of goods at a priori unknown positions. To remedy the unpredictability of

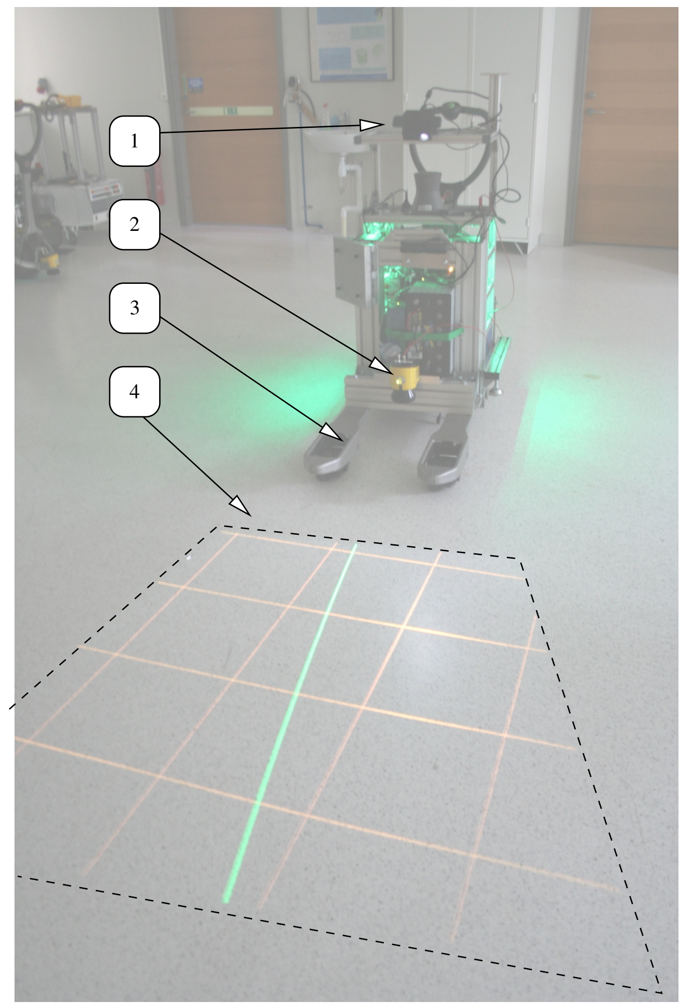


Fig. 1. The platform used for the evaluations: A standard projector (Optoma ML 750) (1) is mounted on a retrofitted Linde CitiTruck AGV (3). The projector is used to project the intention of the vehicle on the ground plane in front of the truck (4). Two SICK S300 scanners are mounted in front (2) and back to ensure safety for human co-workers.

freely navigating vehicles to human workers, an issue that needs to be investigated is the communication of the vehicle's

978-1-4673-9163-4/15/$31.00 © 2015 IEEE

intention. Robot communication abilities will not only increase safety and decrease the stress of the workers, but ultimately result in a better throughput. How easy it is to interpret the intention of the vehicle is highly related to the surroundings. In this context the most difficult cases are found in open environments where very few or no constraints are imposed, as opposed to narrow aisles of pallet racks where AGV motion, although not predefined, is heavily constrained.

The rest of this work is organized as follows: Section II gives an overview of the literature related to applications of Augmented Reality (AR) in robotics, attributes that are important for a natural human-robot interaction and implementations of spatial augmented reality in related applications. Section III explains the hardware and software setup needed to communicate the robot's intentions on the shared floor space. Section IV describes the experiments designed to evaluate the proposed intention communication system followed by Section V, which showcases the results and summarizes the main outcome of the presented work. The final Section VI discusses the system's performance and briefly describes the plans for future work.

II. Related Work

Human-robot interaction has been widely studied for decades, focusing mostly on human intention recognition from the perspective of a robot. However, the contrary situation of robot intention recognition from the perspective of a human has received comparatively little attention so far. A robot communicating its intentions to users in its vicinity allows for a better understanding of the robot while avoiding the unpredictability and communication gap issues. For an effective natural human-robot interaction, Breazeal et al. [1] stress the importance of overlapping perceptual space, appropriate interaction distance and safety. Researchers like Norman [2], Asada et al. [3], Dautenhahn [4], Bates [5] and Blumberg [6] suggest that a robot's ability to communicate effectively will make it appear more reliable, predictable and transparent to humans. In turn, these communication abilities increase a user's willingness towards using the technology and eventually increases the chances of acceptance at the workplace.

Usage of AR techniques has proven to be an effective method of enabling robot-human communication. Milgram et al. [7] was one of the first researchers to implement these techniques in tele-robotic control operations which were further developed by Hine et al. [8], Kelly et al. [9] and Livatino et al. [10]. The most popular way of integrating AR is via head mounted displays which, for several reasons, is infeasible in industrial environments. Instead, we chose to develop a spatial AR system which projects the robot's intention directly into the real environment.

One of the few applications of using AR for communication purposes in robotics – to aid human operators in a human-robot co-worker assembly scenario – was recently proposed by Rüther et al. [11]. Daily et al. [12] used head-mounted AR displays for communicating information to humans from large numbers of small-scale robots in a robot swarm to enable situation awareness, monitoring, control for surveillance, reconnaissance, hazard detection and path finding. Fabrizio et al. [13] and Collett et al. [14] used interactive AR to represent a practical, interactive system for visualizing the internal and normally hidden states of the swarm, overlaid in real-time over a live video feed acquired from a fixed camera. This projection of internal states was used for analysis and debugging processes.

With respect to our work, the most relevant developments are done by Matsumaru [15], Florian [16], Lee et al. [17], Park and Kim [18], Costa et al. [19] and Coovert et al. [20]. They have developed spatial AR systems to project the intentions of a robot on the shared floor space to enable a user to understand the data and behavior of a robotic assistant, thus providing an opportunity to analyze and potentially optimize the working process. The works in [20], [19] performed tests in a real environment, which showcased encouraging results regarding the usefulness of communicating robot intentions. The authors of [15] introduced a mobile robotic system which presents the scheduled path and basic operation states to the people nearby. Also, they conducted a questionnaire evaluation on 200 people about the direction of motion and the speed of motion only, which indicated that the employed AR system made the robot's intents more intelligible. In [18] the idea of a projector based interface to interact with the robot was proposed.

Coovert et al. [20] focused on evaluating the robot's ability to communicate intended movements to a human by asking questions about what the robot's intention might be, while the work in [19] focused more on developing interactive AR interfaces for mobile robots to be used in rehabilitation applications. We have evaluated the mobile robot's ability based on the test subject's reaction in a close to real life situation. Hence, the contributions of our paper are an implementation of a spatial augmented reality visualization system for a mobile platform and a practical evaluation of this system by mimicking a real life scenario.

III. Proposed Approach

The main objective of this work is to communicate the intention of a fork-lift type vehicle, such as the research prototype depicted in Fig. 1, to humans in the vicinity. Ideally, the coverage of the projected floor space should enclose the area around the vehicle and be sufficiently large to allow displaying the intention of the vehicle over a time horizon of several seconds. In the initial evaluation performed in this work, a standard projector was mounted pointing in the direction of the forks as shown in Fig. 1. Thus, both the Field of View (FOV) and illumination brightness are limiting factors. For example, to obtain a large enough projection area, the projector was tilted resulting in some non-illuminated area between the vehicle and the projected image on the floor. This is acceptable because even though the robot's path is generated on the fly, the motion of the vehicle is highly predictable in its close vicinity. The projector is connected to an on-board computer which renders images using an available pose estimate of the vehicle's location together with information regarding the current mission.

A. Vehicle Platform

The mobile base is built upon a manually operated forklift which originally was equipped with motorized forks and a drive wheel only. The forklift has subsequently been retrofitted

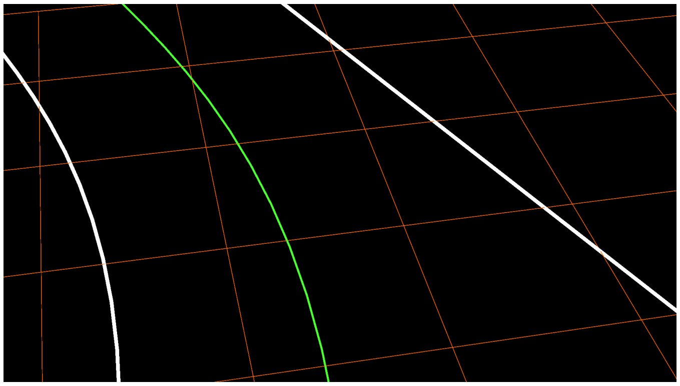


Fig. 2. Rendered image to be displayed with the projector. The dark red grid is of size 0.15 x 0.15 m^2. The green line represents the intended trajectory to be driven and the white lines contain the region that the vehicle needs to occupy in order to traverse the path (green).

with a steering mechanism and a commercial AGV control system. The latter is used to interface the original drive mechanism, as well as the steering servo. To assure safe operation, the vehicle is equipped with two SICK S300 safety laser scanners[1] respectively facing in forward and backward directions.

B. Projected Pattern

In order to render projection images the GLUT framework is utilized. A common reference frame is used in the rendering of the scene and in the overall architecture [21].

This approach makes it straightforward to draw the common 3D world representation by updating the pose of the projector/virtual camera by using the localization estimate of the AGV and the extrinsic parameters ($i.e.$, the pose of the projector/virtual camera expressed in an AGV-fixed coordinate frame). An example of a rendered image that is used for projection is depicted in Fig. 2. The projected red squares remain stationary even when the vehicle is moving.

C. Calibration

There are two steps in drawing the pattern onto the floor. First, we render the image using the GLUT frame work which results in a full screen image. This image looks different depending on where in the virtual world we place the virtual camera. We project the rendered image (full screen) from the virtual camera onto the floor. Another essential part is therefore to determine the parameters of the projector such as its focal length and aspect ratio. Note also that the aspect ratio is dependent on the resolution of the graphics card used to render the image. The goal of the calibration procedure is to be able to consistently place a virtual camera in the GLUT drawing framework such as to generate an image which corresponds to 3D coordinates in the real world when projected on the floor.

The key function of a projector is to display an undistorted image onto a flat surface. Therefore, in this work, we utilize the standard perspective pin-hole camera model [22] to describe the transformation from the image to the projected image in a given reference frame. The standard rendering components available in the OpenGL framework are used to render the image to be projected. The pin hole camera model is described using a camera projection matrix $\mathbf{P}$ which expresses the mapping from a 3D position $\mathbf{x}$ to a 2D image coordinate $\mathbf{y}$ expressed in homogeneous coordinates. The projection matrix is computed as

$$\mathbf{P} = \mathbf{A}\left(\mathbf{R}|\mathbf{T}\right) = \begin{pmatrix} f_x & 0 & x_0 \\ 0 & f_y & y_0 \\ 0 & 0 & 1 \end{pmatrix} \left(\mathbf{R}|\mathbf{T}\right), \quad (1)$$

where $f_{x,y}$ are the focal lengths, x_0, y_0 is the center of the projectors coordinates in pixels and $\mathbf{R}, \mathbf{T}$ describe the pose of the projector (rotation $\mathbf{R}$ and position $\mathbf{t} = -\mathbf{R}^T\mathbf{T}$ in the world coordinate frame). Here $\mathbf{A}$ is the matrix of intrinsic parameters and $(\mathbf{R}|\mathbf{T})$ the matrix of extrinsic parameters.

In this work we have two projection matrices; the first from the virtual camera $\mathbf{P}_C$ which is used to render the scene and the second representing the projector $\mathbf{P}_P$. Given a 3D point $\boldsymbol{x}_C$ in OpenGL, a 2D image coordinate $\mathbf{y}$ and the corresponding projected 3D coordinate $\mathbf{x}_P$, the following relation holds in case of a pin-hole projection model:

$$\mathbf{y} = \mathbf{P}_C\mathbf{x}_C = \mathbf{P}_P\mathbf{x}_P. \quad (2)$$

The main goal of the calibration procedure is to find the transition between the vehicle origin (in the real world) and the OpenGL frame to render the image. Given the projection matrices the transition can be computed as:

$$\mathbf{x}_P = \mathbf{P}_P^{-1}\mathbf{P}_C\mathbf{x}_C. \quad (3)$$

The main problem lies in obtaining the projection matrices. For the projector matrix $\mathbf{P}_P$ we need to find the extrinsic offset $(\mathbf{R}|\mathbf{T})$ as well as the intrinsic parameters $\mathbf{A}$. For the virtual camera $\mathbf{P}_C$ finding the intrinsic parameters can easily be done using the parameters in the ray-tracing method with the screen resolution. To determine the projection matrix for the projector is, however, not straight forward. Since the initial hardware setup only contained the projector and no other sensor which could be used for an automatic calibration procedure, we use a manual calibration approach which essentially works by measuring the projected pattern on the floor. This simple approach could be extended to an automatic procedure.

To simplify the calibration procedure we propose the following approach: firstly, we are not interested in obtaining the projection matrices $\mathbf{P}_C, \mathbf{P}_P$ individually. Secondly, we are also not interested in the factorization of the projection matrices $\mathbf{P}$ into intrinsic $\mathbf{A}$ and extrinsic parameters $(\mathbf{R}|\mathbf{T})$. Instead, our calibration parameters will consist of 7 variables in total; 6 parameters to describe the pose of the virtual camera in the GLUT framework and a scale parameter s, which is used to tune the aspect ratio of the projected image. This scale parameter is directly related to the ratio of the focal lengths f_x/f_y and the focal lengths can be altered by moving the camera back and forth along the viewing axis. The center of projection x_0, y_0 is directly incorporated into the extrinsic parameters (please note that the center of projection only determines where in the image plane the extrinsic parameters refer to).

To give an intuitive movement of the virtual camera for the user in the OpenGL framework during calibration, an orbit

[1]http://www.sick.com/

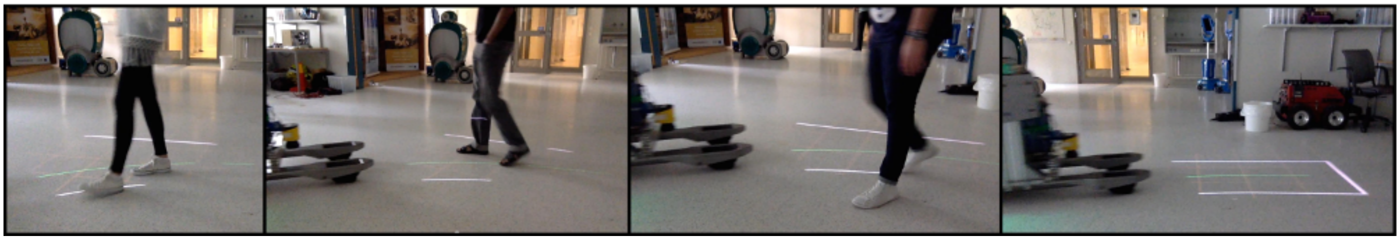


Fig. 3. Photos taken during different stages with different subjects during pilot experiment 2 involving a sharp turn;

type of camera is utilized where the pose is represented using a focal point on the floor $(x, y, 0)$ a distance r and roll, pitch and yaw orientations of the camera. The first step is to use the pitch and roll parameters to adjust the pose to get a pattern with parallel lines on the floor. Next, we use the yaw parameter in order to orient the direction to make the coordinate axes aligned. The third step is to use the distance parameter r and the scale parameter s to obtain projected squares on the floor which are of correct size. Finally, we move the focal point in the (x, y)-plane to get the position of the coordinate system aligned.

The pose of the projector will be computed later on using the global localization estimates of the vehicle and the pose of the projector relative to the reference frame of the vehicle. Therefore, the calibration will be relative to the origin of the vehicle.

IV. Evaluation

In order to understand how useful this technology can be to establish a sustainable human-robot interaction, our aim is to determine quantitatively how humans react to the robot's intentions projected on the shared floor space. Two pilot experiments were designed around real world scenarios to test the key attributes that contribute to a synergistic robot-human work environment. The chosen key attributes along with their respective measured abilities are communication, to measure the robot's ability to convey information to humans, reliability, to measure the robot's ability to encourage trust in humans, predictability, to measure the robot's ability to make humans comfortable around the robot, transparency, to measure the robot's ability to intentionally share the information and situation awareness, to measure the robot's ability to convey necessary information corresponding to the current situation.

In each pilot experiment, as soon as the robot starts moving, the test subject was asked to start walking towards the robot until no longer comfortable with the approaching robot. Every test subject was later asked to rate their experience with the robot on a scale of 1 to 7 with respect to the chosen key attributes. A total number of 13 subjects were chosen from a wide spectrum of backgrounds and ages, such as students, social workers, socio-economists, administration workers, researchers and engineers. Only two of them had some experience with robots but not in particular with the robot employed in the experiments.

The obtained data was used to measure the level of human reactions. Necessary safety precautions were taken during all the pilot experiments and all the test subjects were informed about the potential risks and how to behave in safety critical situations. The maximum velocity of the vehicle was limited to 0.6 m/s during all evaluations.

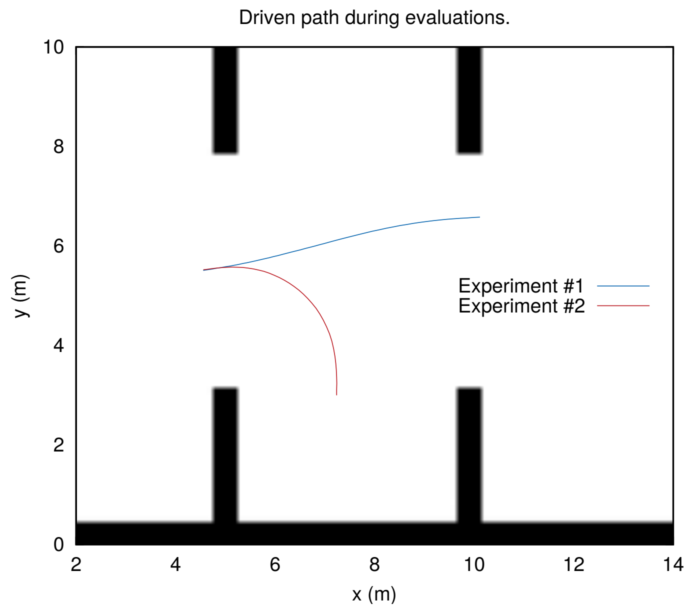


Fig. 4. Driven paths for the two setups. For the first set of experiments the path was almost straight, whereas the second set of experiments involved a sharper turn.

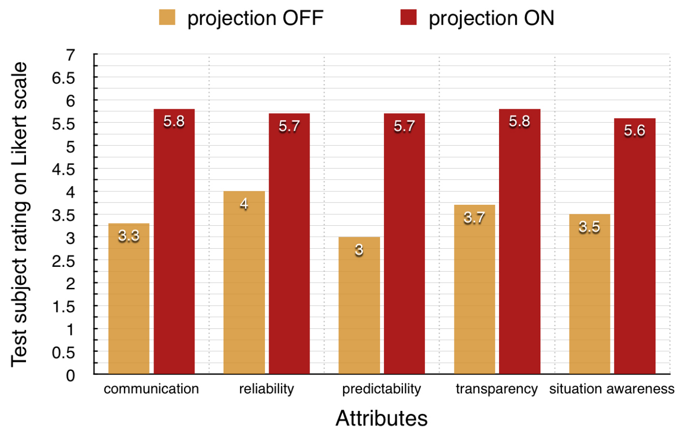
A. Pilot Experiment 1

Pilot experiment 1 essentially constituted a chicken game and was sub-divided into two parts. In pilot experiment 1.1 the robot moved in a straight line without projecting its intentions, while the test subject was asked to walk in a straight line towards the robot and to veer off her path when no longer comfortable with the approaching robot.

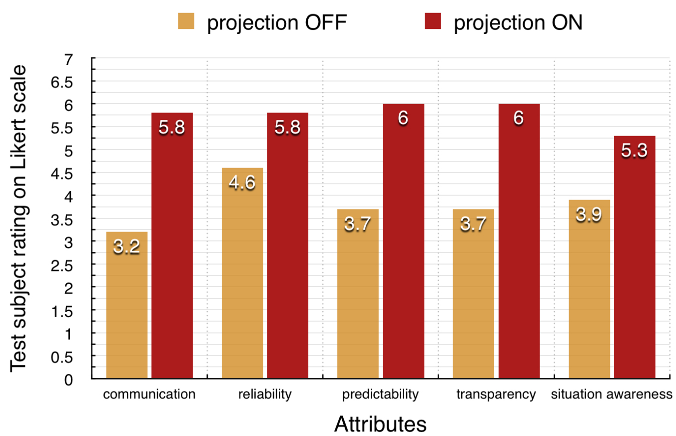
Pilot experiment 1.2 is the same as above with the addition that the robot projected it's intentions onto the shared floor space.

B. Pilot Experiment 2

Pilot experiment 2 is sub-divided into two parts as well. In pilot experiment 2.1 the robot makes a sharp turn without projecting its intentions. The test subject was asked to initially walk towards the robot in a straight line and, after the robot initiated its turn, to veer off in the opposite direction.



(a) Experiment 1, straight path;



(b) Experiment 2, path with turn;

Fig. 5. Response of the 13 test subjects to the questionnaire: the improvement in the ratings when the robot's intentions are projected is evident.

Again, pilot experiment 2.2 is the same as above, with the addition of the robot indicating its intentions.

The paths driven by the robot in the two respective experiment sets are illustrated in Fig. 4. An exemplary test run sequence is shown in Fig. 3. In all experimental test runs the projector was first switched off before switching it on in the corresponding second run.

V. RESULTS

In both pilot experiments, a significant change in the human reaction was apparent when the robot projected its intentions on the shared floor space. This is in strong agreement with the hypothesis that expressing the essential states of the robot is important for a natural human-robot interaction to take place.

When the robot projected its intentions in the pilot experiment 1.2, there was an average increase of 53% in user ratings compared to pilot experiment 1.1, in which the robot did not convey any intentions. Of the attributes considered, communication, predictability and transparency are the most vital components for the acceptability of a robot technology into a human-robot work environment and they achieved significant increases with communication at 81% and predictability as well as transparency at 62%.

TABLE I. VEER-OFF DISTANCE MEAN AND 1-STD VALUES

	Exp 1.1	Exp 1.2	Exp 2.1	Exp 2.2
$\overline{d}\ [m]$	1.40 ± 0.45	2.01 ± 0.79	1.45 ± 0.33	1.81 ± 0.58

TABLE II. PAIRED SAMPLE T-TEST RESULTS

	$\overline{\Delta d}\ [m]$	t	p	$c_i\ [m]$
Exp. 1	0.68 ± 0.78	3.17	0.008	$[0.21, 1.15]$
Exp. 2	0.37 ± 0.37	3.55	0.004	$[0.14, 0.59]$

For the pilot experiment 2, which is a somewhat more complex and practical scenario, there was a larger increase in the average ratings than in the previous pilot experiment. When the robot projected its intentions in pilot experiment 2.2, there was a 65% increase in the average user rating over all the considered attributes. Here, communication, predictability and transparency achieved over 90% rise.

The results summarized in Fig. 5 indicate that the communication system installed on the robot to project its intentions have been a valuable utility for humans in the presence of the robot. This supports our hypothesis that a robot exhibiting its internal states is an asset for the technology's acceptance at shared work scenarios and can aid in achieving harmonious work environments.

In addition to the subjective questionnaires, the subject's trajectory during the experiment was recorded using the laser scanner of the robot and subsequently analyzed. During the pilot experiments, the point where the subject starts to veer-off from the robot's intended path was identified and the distance d between this point and the robot was measured. Intuitively, one would expect the test subjects to approach closer to the robot in case the projection is enabled. However, the obtained results proved the contrary as shown in Table I which summarizes the mean and 1-STD of the distance values for the four experiment sets. A possible explanation for this could be that if humans are aware of future intentions of the robot, they are able to plan their path ahead as well which is beneficial in applied scenarios. A look at the trajectories extracted from the laser scanner data, corroborates this point. When the projection is ON, subjects had planned their path in advance and had a comfortable encounter with the robot instead of a hasty deviation as exemplary shown in Fig. 6. This observation relates to the positive experiences the test subjects had when the projection was enabled as argued previously. It is worth noting that also the distance variance increased with the projection enabled as the test subjects adopted varying reaction behaviors. To ascertain the statistical significance we conducted a paired sample t-test with a significance level of $\alpha = 0.05$. The results are summarized in Table II where $|\Delta d|$ denotes the mean and 1-STD of the veer-off distance differences between experiments conducted wit the projection turned on and off respectively, t indicates the test statistics, p denotes the p-value and c_i describes the corresponding confidence intervals.

VI. DISCUSSION AND FUTURE WORK

Enabling the robot to communicate its internal states has proven to be a valuable added feature for the employed mobile

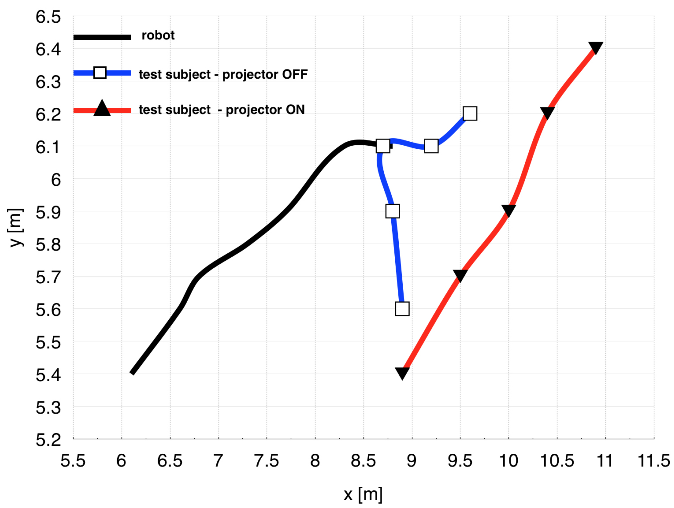


Fig. 6. Exemplary trajectories of the robot and a human test subject from pilot experiment 1. Red trajectories represent projection is OFF and blue represents projection is ON.

robotic system and similar ways of expression methods can be developed for other types of mobile robots as well. By adding simple information such as the future trajectory of the mobile robot and safe paths around it, this mode of communication was able to achieve an effective enhancement in terms of human reaction and we are in the process of enriching this further through enhanced spatial augmented reality visualizations, which can revamp the ways humans interact with mobile robots. Future work will mainly focus on evaluating what needs to be projected and evaluating the system in an industrial environment upon installing the suitable hardware.

Furthermore, we are planning to implement the presented AR system for human-robot communication in an industrial environment, by augmenting it with the capability to project person specific information and provide an intuitive way to interact with the robot. The key technology with respect to the implementation of our approach is the projection system. For the presented implementation, a standard LED projector was used. We have plans to experiment with a combination of other technologies such as pico-projectors, laser projectors and holographic projectors.

Acknowledgements

This work has partly been supported by the Swedish Knowledge Foundation under contract number 20140220 (AIR) and the European Commission under contract number FP7-ICT-600877 (SPENCER).

References

[1] C. Breazeal, A. Edsinger, P. M. Fitzpatrick, and B. Scassellati, “Active vision for sociable robots.” *IEEE Transactions on Systems, Man, and Cybernetics, Part A*, vol. 31, no. 5, pp. 443–453, 2001.

[2] D. A. Norman, *The design of everyday things*. Basic Books, 2002.

[3] H. Asada, M. Branicky, C. Carignan, H. Christensen, R. Fearing, W. Hamel, J. Hollerbach, S. LaValle, M. Mason, B. Nelson, G. Pratt, A. Requicha, B. Ruddy, M. Sitti, G. Sukhatme, R. Tedrake, R. Voyles, and M. Zhang, “A roadmap for US robotics: From internet to robotics,” *Computing Community Consortium on Emerging Technologies and Trends*, 2009.

[4] K. Dautenhahn, “Socially intelligent robots: dimensions of human–robot interaction,” *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 362, no. 1480, pp. 679–704, 2007.

[5] J. Bates, “The role of emotion in believable agents,” *Communications of the ACM*, vol. 37, no. 7, pp. 122–125, 1994.

[6] B. Blumberg, “Old tricks, new dogs: Ethology and interactive creatures. media lab,” 1996.

[7] P. Milgram, S. Zhai, D. Drascic, and J. Grodski, “Applications of augmented reality for human-robot communication,” in *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 3, 1993, pp. 1467–1472.

[8] B. Hine, P. Hontalas, T. Fong, L. Piguet, E. Nygren, and A. Kline, “Vevi: A virtual environment teleoperations interface for planetary exploration,” SAE Technical Paper, Tech. Rep., 1995.

[9] A. Kelly, N. Chan, H. Herman, D. Huber, R. Meyers, P. Rander, R. Warner, J. Ziglar, and E. Capstick, “Real-time photorealistic virtualized reality interface for remote mobile robot control,” *International Journal of Robotics Research*, vol. 30, no. 3, pp. 384–404, 2011.

[10] S. Livatino, F. Banno, and G. Muscato, “3-d integration of robot vision and laser data with semiautomatic calibration in augmented reality stereoscopic visual interface,” *IEEE Transactions on Industrial Informatics*, vol. 8, no. 1, pp. 69–77, 2012.

[11] S. Rüther, T. Hermann, M. Mracek, S. Kopp, and J. Steil, “An assistance system for guiding workers in central sterilization supply departments,” in *Proc. of the International Conference on Pervasive Technologies Related to Assistive Environments*, 2013, p. 3.

[12] M. Daily, Y. Cho, K. Martin, and D. Payton, “World embedded interfaces for human-robot interaction,” in *Proc. of the Hawaii International Conference on System Sciences*, 2003, pp. 6–pp.

[13] F. Ghiringhelli, J. Guzzi, G. A. Di Caro, V. Caglioti, L. M. Gambardella, and A. Giusti, “Interactive augmented reality for understanding and analyzing multi-robot systems,” in *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2014, pp. 1195–1201.

[14] T. Collett and B. A. MacDonald, “Augmented reality visualisation for player,” in *Proc. of the IEEE International Conference on Robotics and Automation*, 2006, pp. 3954–3959.

[15] K. Matsumaru, “Mobile robot with preliminary-announcement and display function of forthcoming motion using projection equipment,” in *Proc. of the IEEE International Symposium on Robot and Human Interactive Communication*, 2006, pp. 443–450.

[16] F. Leutert, C. Herrmann, and K. Schilling, “A spatial augmented reality system for intuitive display of robotic data,” in *Proc. of the ACM/IEEE International Conference on Human-robot Interaction*, 2013, pp. 179–180.

[17] J.-H. Lee, J. Kim, and H. Kim, “A note on hybrid control of robotic spatial augmented reality,” in *Proc. of the International Conference on Ubiquitous Robots and Ambient Intelligence*, 2011, pp. 621–626.

[18] J. Park and G. Kim, “Robots with projectors: An alternative to anthropomorphic hri,” in *Proc. of the ACM/IEEE International Conference on Human-robot Interaction*, March 2009, pp. 221–222.

[19] N. Costa and A. Arsenio, “Augmented reality behind the wheel - human interactive assistance by mobile robots,” in *Proc. of the International Conference on Automation, Robotics and Applications*, 2015, pp. 63–69.

[20] 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.

[21] H. Andreasson, J. Saarinen, M. Cirillo, T. Stoyanov, and A. J. Lilienthal, “Fast, continuous state path smoothing to improve navigation accuracy,” in *Proc. of the IEEE International Conference on Robotics and Automation*, 2015, pp. 662–669.

[22] D. A. Forsyth and J. Ponce, “A modern approach,” *Computer Vision: A Modern Approach*, 2003.