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# A Laser Projection System for Robot Intention Communication and Human Robot Interaction

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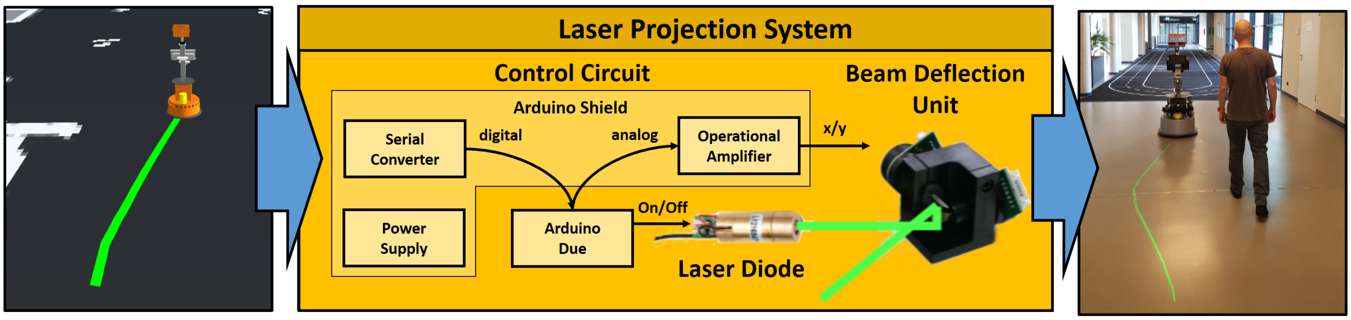


Fig. 1: A service robot projects its planned driving trajectory with the developed laser projection system onto the ground to signalize a person on which side it wants to pass the human. Left: Internal data representation of the robot. Middle: Projection system receives this information to control a laser diode and a beam deflection unit. Right: Resulting projection in the environment.

***Abstract*— In order to deploy service robots in environments where they encounter and/or cooperate with persons, one important key factor is human acceptance. Hence, information on which upcoming actions of the robot are based has to be made transparent and understandable to the human. However, considering the restricted power resources of mobile robot platforms, systems for visualization not only have to be expressive but also energy efficient. In this paper, we applied the well-known technique of laser scanning on a mobile robot to create a novel system for intention visualization and human-robot-interaction. We conducted user tests to compare our system to a low-power consuming LED video projector solution in order to evaluate the suitability for mobile platforms and to get human impressions of both systems. We can show that the presented system is preferred by most users in a dynamic test setup on a mobile platform.**

## I. INTRODUCTION

The main focus of our research targets the development and long-term deployment of robots for challenging real-world scenarios. The fields for application range from supermarket [1, 2] and clinical [3, 4] to domestic [5, 6] environments.In all cases, the transparency of the robot's inner state as well as its intention should improve its acceptance from users or other persons. In our project ROGER [3] for example, where robot-supported mobile walking exercises were performed, a user needs to keep a desired distance to the robot, in order to robustly estimate his or her gait patterns and give reliable feedback. In this case, it could be beneficial to project the area where the user is preferred to walk. In other, less user-centered applications, like our project ROTATOR [1], where a robot is supposed to scan shelfs in a supermarket for out-of-stocks during opening hours, the acceptance and subjective sense of safety could be increased by visualizing the robot's planned driving trajectory.

For such visualization purposes, robotic applications from the literature, like [7–12], have already made use of video projectors for human-robot interaction. However, these video projector solutions have some critical drawbacks for their mobile applicability. Even though there are relatively low power consuming LED video projectors available at the market, like the Telefunken DLP400, which we have previously utilized in our projects, this video projector (33W) still needs $\approx$ 15% of the total power consumption ($\approx$ 220W) of our robot. This reduces the robot's effective operation time and, thus, is a suboptimal solution for long-term applications. Furthermore, due to the LED backlight technology there is always an illuminated area and thus, power is always consumed, even when no information is projected (i.e. the video projector's image is empty). This can also be problematic since this area may lead to misinterpretations by the users (see Fig. 2). Moreover, the opening angle of the LED video projector is relatively small and the illuminescence is inversely proportional to the square of the distance to the projector. This restricts the projections to an area directly in front of the robot. User tests in our shelf out-of-stock detection

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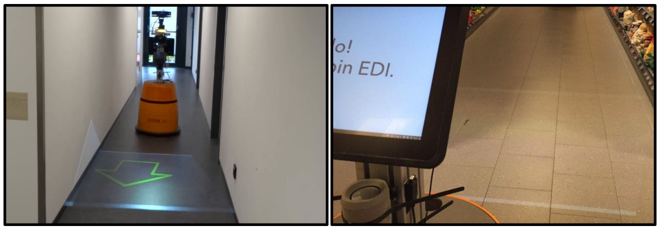


Fig. 2: Robot and projections with the previously used LED video projector solution. Left: Arrow visualization in our lab. Right: illuminated area in one of the targeted environments.

project with a Telefunken DLP400 [1] have confirmed these disadvantages in a supermarket application. The brightness of the video projector is too low and, thus, users asked for a higher contrast.

In this paper, we present an alternative to conventional video projector solutions for robotic applications based on a deflected laser beam. Deflecting a laser beam, also called laser scanning, is common practice in a wide field of applications, ranging from laser range measurements (lidar) over barcode scanning to laser shows. However, to the best of our knowledge, this technology has never been used for human-robot-interaction on a mobile robot. The main advantages of our system, in comparison to conventional video projector solutions, are as follows. Since the inverse-square law for light in form of a bundled laser beam is negligible, larger projection areas and distances can be achieved. In addition, our system is more energy efficient and requires only about 1/3 of the reference video projector's power consumption at maximum.

In summary, the contributions of this paper are:

- the development of a laser projection system suitable for deployment on mobile platforms, consisting of a galvanometer laser scanner, a self-designed circuit board, and software to control the laser beam,
- the publication of circuit board designs and micro-controller code to the scientific community[1],
- an user evaluation of the laser projection system in comparison to a common LED video projector with respect to perceptibility and usability

## II. RELATED WORKS

Visual signals for human robot communication have been studied over the last two decades. Robots with artificial heads for example can signal their driving direction [13]. However, this is a relatively limited method for communication. Also blinking LEDs have been used for this purpose [14], but have shown least understandability compared to other intention cues like motion and speech. Robots with artificial eyes [15] may use facial expressions to show intentions, but results have shown that they are hard to interpret by humans. The usage of video projector solutions for human robot interaction has shown great advantages in static [16, 17] setups. Also in mobile applications, video projectors have been deployed in a wide variety of areas. In [8, 11] robots for guiding tasks that project useful information to users into the environment are described (e.g. the direction a user should look at). Other works made use of a video projector to visualize the robot's driving behavior, either by projecting the desired driving direction [12] or the planned local path [9] in front of the robot. Considering service robots in domestic environments, [7] used a video projector in combination with a Kinect2 sensor to project information about a recognized object onto the object's 3D surface. Even video conference systems and workout supporting video projections have been deployed in an ambient assisted living scenario with a mobile robot [10]. However, while in static scenarios the power consumption of a video projector is not an issue, in mobile setups it is. An increased energy consumption leads to a lowered effective operation time and, thus, to a decreased effectiveness of the robot. In the following, we present an alternative to power consuming video projector solutions suitable for mobile applications.

## III. SYSTEM DESCRIPTION

The principle of laser scanning is to deflect a laser beam in x- and y- direction, using two fast-rotating mirrors. In our system we use a so called galvanometer scanner for that purpose (see Fig. 1), that is controlled using several hard- and software modules. For a projection, the scanner receives a list of 2D coordinates on which the laser beam is pointed. When all points are processed, the scanner repeats the list until a new projection shall be displayed. If the deflection is fast enough, the projection is perceived as a continuous figure by humans.

In the following, we describe this system more in detail. First, we present the constructed hardware and the micro-controller that was integrated on our robot. Then, we describe the software modules that transform the internal data representation of the robot to a list of 2D points that is received by the deflector. Finally, we give an overview of the implemented visualizations that were tested in the experimental section.

### A. Hardware

Our hardware construction consists of three independent main components, which are illustrated in Fig. 1: The laser diode, the beam deflection unit, and a control circuit. The first two are off-the-shelf components whereas the latter is a custom built circuit, that we made publicly available[1]. The system uses a standard USB interface, allowing an easy connection with our robots.

**Laser diode:** For a laser projector, the perceived brightness of the projection depends on its size and the power of the laser diode. Since, under normal lighting conditions, greenish colors are perceived best by humans [18], we also decided in favor of a green laser diode. For our experiments we used a $5\mathrm{mW}$ green laser diode of class 3R from TRU Components (LM05GND, $532\mathrm{nm}$ wavelength). We have chosen a class 3R laser since it provides the highest brightness and is

[1] https://www.tu-ilmenau.de/neurob/data-sets-code/laserprojector/

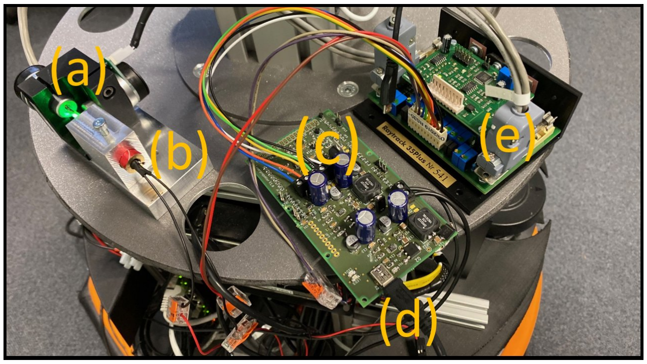



Fig. 3: Experimental construction of the laser projector: Beam deflection unit (a) and the laser diode (b) are mounted onto an aluminum plate, our developed interface circuit (c) with USB connection (d), the provided galvanometer control unit (e) which comes with the beam deflection unit.

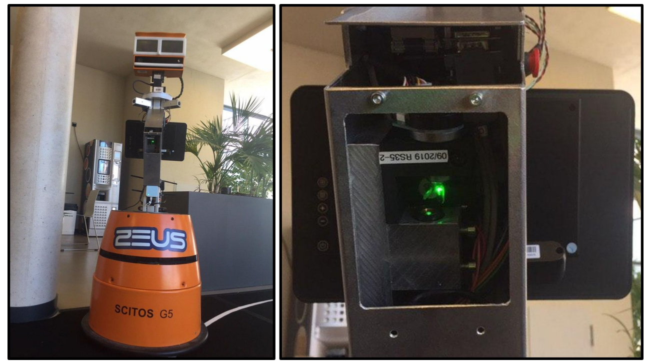



Fig. 4: Left: Final integration of the laser projection system in an aluminum case on the ROTATOR robot [1]. Right: Closeup of the beam deflection unit.

classified as eye-safe for diffuse reflections[2]. However, it should be avoided to intentionally stare into the direct non-moving beam. Higher powered laser diodes offer even more brightness and could be integrated as well. However, additional precautions need to be taken with laser classes 3B and 4, as these lasers can easily cause damage to the human eye if they hit the human eye directly or indirectly.

If more than one object shall be projected simultaneously, the mirrors need to move between these whilst the laser diode is turned off, as otherwise a line would connect the objects. Thus the laser diode has to react to a control signal as fast as possible, i.e. within the time between consecutive points, which we set to 50 microseconds. As our laser module does not provide these low switching times with the supplied driver, we replaced it with a logic level laser-driver. Hence, the laser diode's current is regulated by the driver and the control circuit only needs to provide a single binary signal (e.g. 3.3V for laser on and 0.0V for laser off).

**Beam deflection unit:** For beam deflection a K12n low-cost-scanner from JMLaser is used. It consists of two high speed galvanometers which are each connected to a small mirror. We measured an optical opening angle of $\pm 27°$ for both axes. Note that this is $\pm 7°$ larger than declared in the technical specifications of this module. The galvanometers are controlled by an integrated circuit, that complies with the ILDA[3] interface specifications and thus, uses two analog signals ($\pm 10V$) as positional input for the two mirrors. The conversion of the digital point lists from the robot to these analog signals is done by a control circuit that is described in the following.

**Control circuit:** To power and control the laser diode as well as the beam deflection unit, we use an Arduino Due ARM-based microcontroller in combination with a custom-designed arduino shield circuit, that can be plugged on top of the Arduino Due. The shield includes a highly efficient switching power supply unit, which provides the stabilized, symmetrical DC voltage needed by the beam deflection unit ($\pm 18\text{V}$) and the laser diode as well as the Arduino ($+12\text{V}$). The input for the power supply unit is directly taken from the robot's battery ($+22.4\text{V}$ to $+30.4\text{V}$, depending on the current state of charge). Furthermore, the shield includes a high-speed USB-to-Serial-Converter (F232RL from FTDI) that is used to transfer the point lists via USB to the Microprocessor. To output the current projection and receive new data from the robot simultaneously, we use two ring-buffers and interrupt-based programming on the microprocessor.

The coordinates in the point lists (described in Sec. III-B) are converted to analog signals by using the integrated digital-to-analog converters (DACs) of the Arduino Due. The shield then transforms these low-voltage signals ($0.55\text{V}$ to $2.75\text{V}$) to the ILDA levels ($\pm 10\text{V}$) using an operational amplifier circuit. In summary, our control circuit acts as an easy to use interface between the robot's software layer (Sec. III-B) and the aforementioned laser projector components. All those components (Fig. 3) are mounted on our robot inside an aluminum case, providing a stable mounting of all parts as well as a proper cooling of the galvanometer driver circuit and the laser diode (see Fig. 4).

### B. *Software*

In order to visualize internal data representations (e.g. the planned local path or a symbolic object) with the laser projector, they have to be transformed into x-y coordinates (see Fig. 5), which are passed to the control circuit. The control circuit then converts these x-y coordinates to analog signals ($\pm 10\text{V}$), which correspond to specific angles of the mirrors. Furthermore, due to the mounting of the projector, the projection has to be distorted according to its point of view in order to meet the correct proportions in the environment, e.g. on the ground. This is achieved by converting the data representation into a polygon (ordered list of 3D points). To provide a uniform distribution of light in the environment, it has to be ensured that the points of the polygon are evenly distributed over their Euclidean 3D distance. If this

[2]Note that laser safety regulations can be different for each country. We take no responsibility for damage of any kind caused from replicas of our system or specific parts of it.

[3]https://www.ilda.com/

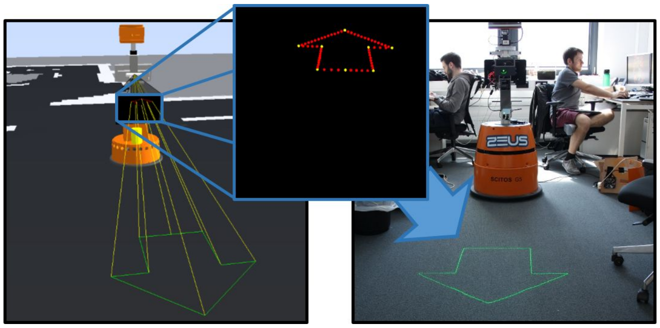


Fig. 5: Left: Virtual arrow polygon in 3D world coordinates. Middle: Backprojected corner points, which define the polygon, in the image plane (yellow) and points that are filled in between the corners (red). Right: Projection in the environment.

is not the case inherently, e.g. for an arrow polygon which is just defined by its corners, we automatically insert new points every $5\mathrm{cm}$. Since each polygon is defined in its own coordinate system, e.g. the robot's coordinate system for the planned local path polygon, the second step is to transform all polygon points into the projector's 3D coordinate system. Finally, to generate the 2D point list for the laser projector, each 3D point of the polygon is projected onto a virtual image plane using a pinhole camera model

$$\begin{pmatrix} x_{2D} \\ y_{2D} \end{pmatrix} = \begin{pmatrix} x_{3D}/z_{3D} \cdot f_x + c_x \\ y_{3D}/z_{3D} \cdot f_y + c_y \end{pmatrix}.$$

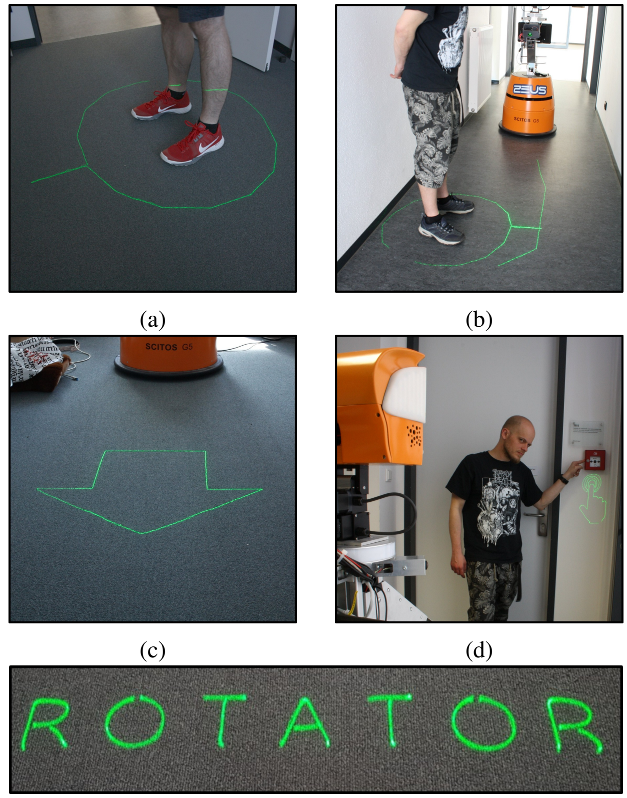
The principal point $c$ is assumed to be in the center of the projector $c_x = c_y = 0.5$. The focal length

$$f = f_x = f_y = \frac{1}{\tan(\phi)}$$

can be determined using the known opening angle $\pm\phi$ of the beam deflection unit.

### C. Implemented Visualizations

To show the internal state and intentions of the robot, we implemented several visualizations. To signal a person that s/he is perceived by the robot, we project the personal space [19] as circle around his/her feet. Furthermore, the estimated upper body orientation is indicated by a small arrowhead (see Fig. 6a). For person perception, we use the tracking system proposed in [20]. The upper body orientation is estimated with the pointcloud and deep learning methods proposed in [21, 22]. To visualize the planned driving behavior, we project either the planned global path [23, 24] or the local trajectory [25, 26], which is used for navigation purposes by our robot (see Fig. 6b). However, these path visualizations have relatively fast changing appearances and, therefore, have shown to be likely misinterpreted in the dynamic user tests (Sec. IV-B). Hence, we implemented an alternative arrow visualization pointing to the desired location that the robot will pass in the next second (see Fig. 6c)). To give additional application-specific information to the user, e.g. that s/he shall push a button (see Fig. 6d), our system is further able to project symbols or text (see Fig. 6e).




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

Fig. 6: Various visualization examples of the laser projector: personal space and person orientation (a), personal space, person orientation and planned path (b), driving direction visualized as arrow (c), arbitrary symbol (d) and text (e).

## IV. EXPERIMENTS

In all test setups, we used a $5\mathrm{mW}$ green laser diode in the developed laser projection system and a low power consuming Telefunken DLP400 as reference for video projector solutions. A comparison of the technical parameters can be found in Table I. To evaluate both projection systems, we conducted two kinds of test procedures. In the first one, the general visibility was evaluated in a static test setup (see. Fig. 7 left). The second one was conducted to evaluate the general usability, by performing dynamic tests on a mobile platform (see. Fig. 7 right). To ensure that the given impressions were not influenced by the preceding experiment, both tests were conducted with different persons. In total, we acquired 16 participants (10 male and 6 female) and split them into two groups with equal size and gender distribution for the static and dynamic tests. All of them were between the age of 18 and 34 years, mostly students with little or no experience with robots. For both test setups, we developed a questionnaire with a set of categorical answers on a five point likert scale. Possible answers were Strongly Agree (SA), Agree (A), Neither Agree Nor Disagree


Fig. 7: Left: Placement of the first prototype of the developed laser projector (a) and reference LED video projector (b) at the robot in the experimental static test setup. Right: A person passing the robot while the planned trajectory is projected to the ground in the dynamic test setup.

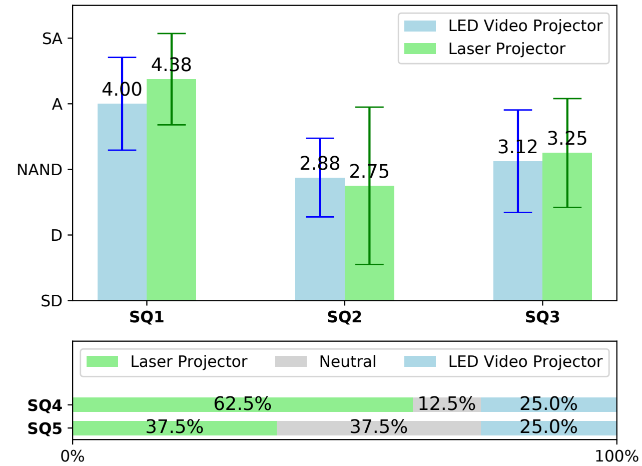
(NAND), Disagree (D), Strongly Disagree (SD). Beside these categorical questions, in both experimental series the participants were asked to give a general preference for either the laser projector or the LED video projector. They were supposed to choose only one answer for each question. Furthermore, it was also possible to give general impressions or additional notes in an interview after the experiments.

### A. Static tests

In the static test setup, we evaluated the general visibility of the developed laser projector in comparison to the previous LED video projector solution on different coverings. The participants were free to walk around to assess the projections from different points of view. All possible visualization options for symbols, text, and the planned trajectory (see Fig. 6) were projected consecutively onto one specific ground. After that, the participants filled out one item of the questionnaire, and the ground was changed to the next one. We tested three floor coverings ranging from light- and dark-colored floor coverings to a dark carpeting ground. Results and items of the static questionnaire (SQ) are shown in Fig. 8. It can be seen, that in this static test setup, the visibility for both projection solutions was rated as good for light-colored floor grounds. For the dark-colored floor covering and carpet,

| Tech. specs. | LED video projector (DLP400) | Developed laser projection system |
|---|---|---|
| opening angle | ±22°H ±13°V | ±27° H/V |
| power consumption | 33W | 5.6W (idle)<br>10W (in operation) |
| colors | RGB | curr. monochromatic |
| brightness | decreases with distance | decreases with vis. complexity |

TABLE I: Comparison of the technical specifications of the LED video projector and the developed laser projection system used in the experiments.



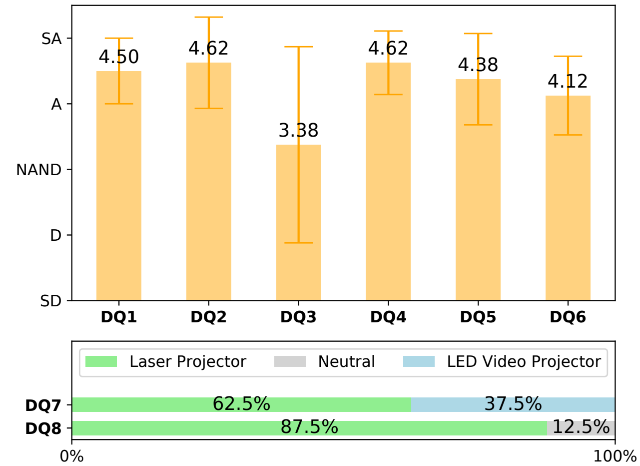

| | |
|---|---|
| **SQ1** | The laser projector / LED video projector provides a good visibility on the **light-colored floor covering**. |
| **SQ2** | The laser projector / LED video projector provides a good visibility on the **dark-colored floor covering**. |
| **SQ3** | The laser projector / LED video projector provides a good visibility on the **dark-colored carpeting**. |
| **SQ4** | Which kind of projector generates more attention? |
| **SQ5** | Which projector would you prefer to communicate information? |

Fig. 8: Results (mean) of our static test questionnaire (top) and corresponding questionnaire items (bottom). Whiskers in the top figure indicate the standard deviation.

the same question was answered indifferent. Furthermore, the test subjects have shown no clear preference for either the laser projector or LED video projector solution. Three participants stated that they preferred the thicker contours of the LED video projector, which the laser projector is not able to display. One participant even preferred the illuminated area of the video projector since it generates more attention. In conclusion for this test setup, the developed laser projector does not achieve a significantly better acceptance than the previously used LED video projector. So, the only advantage, which remains for the laser projector, is the lower power consumption in such a static setup. With these findings, we wanted to evaluate the usability in a dynamic test setup where other characteristics, like the increased opening angle and scene dynamics, came into play.

### B. Dynamic tests

For this test setup, an evasion situation between a robot and a person was initiated. The participants were asked to walk in a straight line to a goal behind the robot (no further instructions were given) while the robot was driving to a goal behind the participant. After the encounter, the persons were asked to answer questions about their experiences in the situation. During these tests, the robot's driving behavior was influenced by persons around him, utilizing an asymmetrical personal space cost function around detected persons. With this driving behavior enabled, the robot avoided to get in close proximity to the persons and preferred to pass persons on the right side, like in a human-human passing-




| | |
|---|---|
| **DQ1** | The movements of the robot become more predictable through the projection of a projector. |
| **DQ2** | I find the information transfer of the robot through a projector to be good. |
| **DQ3** | With a projector, the robot can gain the trust of humans more quickly. |
| **DQ4** | The path trajectories shown bring added value to the interaction with the robot. |
| **DQ5** | The projections make me feel safer. |
| **DQ6** | The projections give me the feeling of being perceived by the robot. |
| **DQ7** | Which type of projector generates more attention for the situation played through? |
| **DQ8** | Which type of projector is better suited for the situation played through? |

Fig. 9: Results (mean) of our dynamic test questionnaire (top) and corresponding questionnaire items (bottom). Whiskers in the top figure indicate the standard deviation.

Fig. 10: Further visualizations in our ongoing work. Left: walking feet animation to tell a person to leave the elevator. Middle: restricted area no one should enter when the robot enters the elevator. Right: opening animation to signalize that the robots wants to pass the door and requires help [27].

by situation. For a more detailed description of the utilized driving behavior we refer to [1]. The aim of this experiment was to show that the visualization of the driving intention and environmental perception can increase the user acceptance. To visualize the driving intention of the robot, we project the planned path. To signal a person that s/he is perceived by the robot, we utilized the personal space visualization (see Fig. 6a). The experiment was repeated three times, once with no projections, once with the LED video projector, and once with the laser projector. Results and items of the dynamic questionnaire (DQ) are shown in Fig. 9. These results indicate, that projections in general add value to a human-robot-interaction. The participants stated that the movements of the robot became more predictable, they felt saver and perceived by the robot through the utilized projections. Only the question whether the projections can increase the trust of humans was answered indifferent. The reason for this might be the inexperience of the participants with robots in combination with our relatively large experimental platform. However, more interesting was the result of the preference question (DQ8). In contrast to the static tests, in this experimental setup 7 of 8 participants preferred the laser projector instead of the LED video projector solution while one participant was neutral. This can be explained by analyzing the specific remarks from the participants from the interviews. Even though, 3 participants stated that the LED video projector attracts more attention through the illuminated square in front of the robot, this was found to be confusing (4 participants) in the tested situation. One participant even misinterpreted the illuminated square to be scanned by the robot. Three participants stated that the visualization of the planned path is beneficial when interpreting the driving behavior. *"The projection helps with decision making and takes away the fear of getting closer to the robot"* (TP06). However, also three participants found the path projection difficult to interpret at first and asked for an alternative visualization. Therefore, we implemented an arrow projection to indicate the driving direction (see Fig. 6c). However, an evaluation of this new visualization remains part of future work. The visualization of the personal space was mostly found to be useless, since it was either not recognized or too late to achieve the intended effect (8 participants).

## V. CONCLUSION & FUTURE WORK

In this paper, we have presented a novel approach for projecting information into the surroundings of a mobile robot using a laser projection system. The presented system is easy to integrate on any mobile platform that provides the needed power supply and an USB port for controlling. We compared the laser projector with a convenient LED video projector solution suitable for robotic applications. We performed an assessment of the perceptibility and usability in two user test scenarios. Results show, that, even though the laser projector with a 5$\mathrm{mW}$ diode is preferred en par with the LED video projector in a static test setup, it achieves a higher acceptance in dynamic HRI situations. Reasons for this are the wider opening angle as well as the higher brightness at greater distances. Moreover, since the laser projector does not illuminate the whole projection area, users are less likely confused. An additional advantage is the lower power consumption, which allows an increased uptime of robots in the application compared to a classic video projector. However, these user tests just give an initial subjective assessment

Fig. 11: Comparison between a $5\mathrm{mW}$ and a $40\mathrm{mW}$ laser diode. Left: The $5\mathrm{mW}$ diode from the user tests. Right: The currently installed $40\mathrm{mW}$ diode for our future work.

of the tested age group in a lab environment. We plan a more extensive user study in the targeted environment [1] with a larger amount of participants and objective measures, like the change of reaction times when passing the robot. Furthermore, in upcoming user tests (planned in August 2020) with our FRAME robot [27] we will evaluate the intention indication when asking a user for assistance to pass closed doors or using an elevator (see Fig. 10). Currently, we are working on the integration of a more advanced beam deflection unit (Raytrack 35+ by JMLaser). Despite an increased opening angle of $\pm 37°$ H/V (measured), this unit also provides an integrated laser safety circuit. The deflector calculates the beam's speed from signals provided by our interface (target position) as well as the current mirror angle (actual position). If a minimum distance is ensured between the user's eye and the beam deflection unit, a minimum speed for eye safety can be determined. The safety circuit ensures that the laser diode is only switched on if the current speed is above the minimum speed for eye safety. This allows the safe usage of higher powered laser diodes and, thus, a better perceivability. Moreover, the power consumption of the diode is negligible in comparison to the rest of the system. First preference tests have shown a much greater acceptance for a system with a $40\mathrm{mW}$ diode (see Fig. 11). Furthermore, we plan to integrate an RGB laser module, consisting of three laser diodes and two dichroic mirrors for beam merging, which will make it possible do project colored symbols.

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