Legible Light Communications for Factory Robots

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ABSTRACT

This work focuses on methods to improve mobile robot legibility in factories using lights. Implementation and evaluation were done at a robotics company that manufactures factory robots that work in human spaces. Three new sets of communicative lights were created and tested on the robots, integrated into the company's software stack and compared to the industry default lights that currently exist on the robots. All three newly designed light sets outperformed the industry default. Insights from this work have been integrated into software releases across North America.

CCS CONCEPTS

• **Human-centered computing** → *Contextual design*; *User studies*;
• **Computer systems organization** → Robotics.

KEYWORDS

human-robot interaction; factory robots; expressive lighting

1 INTRODUCTION

Social robotics has learned a great deal about effective robot communications with people, however, few existing factory robots use these insights in their everyday operations. The research of this paper involved the integration of a social robotics researcher into a robotics company that manufacturers mobile factory robots. The goal was to redesign the robot's light communication system based on social robotics principles. Despite extensive research in both expressive robotics [2–4, 6, 8, 9, 12] and HRI in factory settings [1, 5, 7, 10, 11, 13], there has not been work that utilizes expressive robotics to improve factory robots. This work attempts to bridge that gap by creating expressive lights for the operational challenges of a particular point-to-point transport factory robot.

2 CREATING COMMUNICATIVE LIGHTS

To increase legibility of the robots created at OTTO Motors, new light sets were designed with expression and communication in mind, based on company feedback and previous work in HRI. The new light sets were fully integrated into the software stack of the OTTO 100.

Three custom LED sets were created for the user study: Car-like, Sweeping, and Heartbeat. Car-like and Sweeping were created

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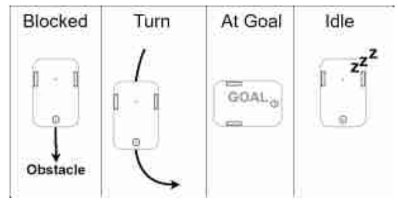

Figure 1: Three new light sets were collaboratively designed with employees of an active factory robot company, and evaluated for legibility across these four robot states.

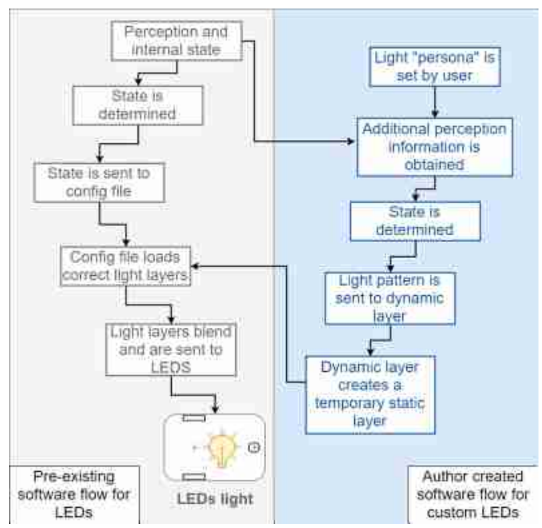

Figure 2: We extended existing software for setting the 340 multicolor-LED strips encircling the robots (on left) to allow for the creation of dynamic, custom LED sets (on right).

based on results of a company wide survey that used a scene-based approach to solicit their design ideas for improved robot expressions. Heartbeat was created based on previous work in HRI. The Industry-default lights were used as a control and compared the three custom light patterns. The colors for the states in the custom set were based on the company survey. Four states were chosen for creating custom lights: "blocked," "turning," "at goal," and "idle," as seen in Fig. 1. These states were chosen because they occur very frequently in normal OTTO 100 operation, both on the test floor and in factory settings.

INDUSTRY-DEFAULT: The pre-existing Industry-default lights consisted of two white corner lights in the front and two red corner lights in the rear, similar to vehicle lights. For turning, a yellow light pulsed along the side the robot was turning towards, otherwise, the lights were static. Light patterns for "blocked," "at goal," and "idle" did not exist in the Industry-default lights.

SWEEPING: Sweeping lights move around the robot and converge to a particular point of interest. Employees suggested that this would act as a legible directional indicator, e.g., "being pulled towards it's goal" or "chasing" its object of attention. We used dashed lines to display the movement as a solid shrinking light can look static from certain angles. The "blocked" lights were red and converged to the obstacle, the "turning" lights were white and moved in the direction of turning, and the "at goal" lights were green.

CAR-LIKE: The Car-like echoed the default, with off-white headlights in the front, and dimmer red lights in the back. Employees suggested that the car analogy would make sense to people for a moving rectangular vehicle. When blocked, the headlights flashed bright white and the back headlights flashed red. When "turning" the headlight and rear light. When "at goal", the headlights and rear lights flashed green. The light colors for each state matched other custom sets so that we could evaluate metaphor rather than color.

HEARTBEAT: This set used pulsing lights around the full circle of the robot echoing previous work [2]. The goal here was to benchmark employee suggestions relative to the state-of-the-art in research. A single color around the entire light strip that pulsed from bright to dim. Red was used for "blocked," white pulsing on the side for "turning," green for "at goal," and dim white for "idle."

To create lights that were activated depending on the context, additional state information and ways to set the LED strip had to be created. To change the lights, a dynamic light layer was written using C++ that listened to a ROS topic of color values, wrote those values to a row of a PNG, and used that PNG to send to the LED strip. Different python scripts were created for each light set that published to the ROS topic. The python scripts controlled the color, spacing, and timing of the lights and when different patterns were activated. The software flow can be seen in Fig. 2.

3 EVALUATION OF LIGHT SETS

To evaluate the three custom light sets against the Industry-default, a user study was run to collect legibility ratings across all light sets.

PROCEDURE In the experiment all participants experienced all four light sets. Each participant saw the Industry-default light set first, then saw the three custom light sets in a random order. To allow the participants to see all the states, the robot made two passes in a large L-shape: one where it was blocked, and another when it had a free path. After each set, participants answered survey questions exploring the legibility of the light sets by state. 30 company workers from the company participated in the user study. Familiarity with the OTTO 100s ranged from having no interaction or familiarity with the light patterns to interacting everyday and knowing all the light patterns and triggers.

MEASURES Participants were asked on a 7 point Likert Scale if they agreed or disagreed with statements about the legibility of the robot. The statements were "*It was clear to me when the robot was {state}* ." -3 corresponded to Strongly Disagree and 3 corresponded to Strongly Agree. Numerical results were calculated and checked for statistical significance using a Friedman test for the within-participants study. This test was used because analyses were run across single Likert scales. For all the degree of freedom was 3 and N = 30. For blocked the results were ($\chi^2 = 57.87, p < 0.0001$).

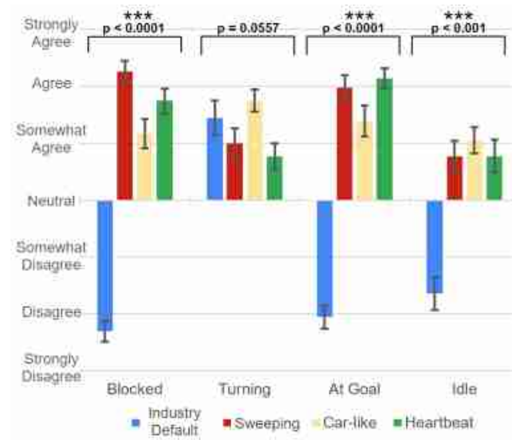

Figure 3: The custom-designed light sets significantly outperformed the legibility of the industry defaults for "blocked," "at goal," and "idle". Mean legibility survey responses displayed with significance between all four sets (p) and standard error.

For "turning" they were ($\chi^2 = 7.57, p = 0.0557$), ($\chi^2 = 52.91, p < 0.0001$) for "at goal" and ($\chi^2 = 36.45, p < 0.0001$) for "idle." Additionally, Dunn's post-test was run to test pairwise significance.

4 RESULTS AND DISCUSSION

The results showed that the custom and research-inspired light sets conveyed the robot's intent and internal state well compared to the industry-default (Fig. 3) with p-values of less than 0.0001. Dunn's test confirmed that the significance was coming from the difference between Industry-default and all the three other pairs for blocked, at goal, and idle, with p-values between pairs less that 0.001. In the short interviews after the user studies, no one chose the Industry-default lights alone as the favorite set they saw.

Overall, car analogies in factory robot lighting are useful for states present in highway driving, such as turning. However, when the robots are in situations that involve interaction or inner state communication, the car analogy breaks down. It is in these cases that alternative light patterns are strongest. In a blocked situation, the attention grabbing moving bars of the Sweeping set were the most effective. Apart from catching a user's attention, this light pattern also allows additional information to be conveyed, such as the direction of the obstacle blocking the robot. At the goal, the calmer pulsing of the Heartbeat was preferred.

Lights for the "blocked" state and "idle" state have already been released to customers in November 2019 as part of an updated industry-default light set, thus factory and warehouse robots operating today have already benefited from this work. For that release, the Car-like lights were chosen because they are visually the closest to the current standard lights, however, a full set of new light patterns may be included as early as spring of 2020. Overall, this work has demonstrated the successful application of HRI research and participatory design to real robots operating in industry, showing the mutual benefits that can come from collaboration of research and industry.

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