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Passive Demonstrations of Light-Based Robot Signals for Improved Human Interpretability

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***Abstract*— When mobile robots navigate crowded, human-populated environments, the potential for conflict arises in the form of intersecting trajectories. This study investigates the use of light-emitting diodes (LEDs) arranged along the chassis of a robot in an arrangement similar to a turn signal on a car as a non-anthropomorphic, yet familiar signal to convey the intended path of a mobile service robot. We study the scenario of a human and a robot heading directly toward each other in a hallway, which may give rise to the familiar human experience in which both parties step to the right, then the left, then the right, continuing to block each other's paths until they are able to coordinate their movements and pass each other. We conducted a pilot study which revealed that people do not always interpret this signal as one may expect, which would be similar to how a car uses its turn signal. This motivated a 2×2 experiment in which the robot either does or does not use LEDs to indicate its intended direction of travel, and in which study participants either are able to or unable to witness the robot's "lane-changing" behavior further down the hallway prior to coming into direct proximal contact with the robot. The results demonstrate that exposing participants to the robot's use of the LED signal only once prior to passing each other in the hallway is sufficient to disambiguate its meaning to the user, and thus greatly enhances its utility in-situ, with no direct instruction or training to the user. These findings suggest a paradigm of passive demonstration of such signals in future applications.**

I. Introduction

The Building-Wide Intelligence (BWI) project at UT Austin seeks to develop mobile service robots, called BWIBots (Figure 1), that can provide assistance to the occupants of the Computer Science Department [1]. With the BWIBots navigating the corridors of the department throughout the workday, a frequent undesirable occurrence is that of a robot and human blocking each other's path. When conflicts arise in this setting, we often find them humorous. Because these robots are research prototypes, we expect to deal with these sorts of issues. In mission-critical applications such as hospitals or even less critical applications such as delivering room service in hotels, the problem of creating such a blocked passage would escalate from being a humorous happenstance to being a show-stopping design flaw. To develop solutions to this problem, we have constructed a test hallway (Figure 2) in a large laboratory space where we study various navigational scenarios in which humans and robots must negotiate shared access to terrain. The work presented in this paper considers the scenario of a human and a robot navigating a corridor from opposite ends in opposing directions, and the potential conflict created when their paths meet.

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Fig. 1: The BWIBot family of robots. Left: V2 with Arm, Center: V3 (the robot used in this study), Right: V2.

The vision of mobile service robots is that they will be able to assist humans in a variety of scenarios and environments by performing a complex assortment of tasks to support day-to-day work, domestic, and care activities. Service robots are expected to provide assistance in domains including the home [2]–[5], space exploration [6], schools, and workplaces [1], [3]–[5], [7], [8]. These robots are often constructed with form factors and appearances that are specialized to the tasks which they perform. Many have a functional, non-humanoid appearance with few to no anthropomorphic features. Gracefully interacting with the people who use these devices will involve studying interaction paradigms that differ from the more well-studied areas of human-robot interaction that are based on humanoid or android robots [9]. Communicating a variety of unique and recognizable signals in situations where humans cannot be trained or where the robot is not directly interacting with any specific person remains challenging [10]–[12]. Common communication modalities available to service robots, such as spoken language and on-screen displays, are limited by proximal constraints and can be ineffective when a person is too far to see the display or hear the robot's voice [11].

This work explores two concepts in non-anthropomorphic HRI. The system, as designed, uses a pair of LED light strips mounted to the robot's chassis to indicate the robot's intended motion trajectory in a fashion similar to the turn signals on a car. The robot's navigation algorithm treats the corridor as being divided into three traffic lanes through which it may navigate. When "changing lanes," the robot signals this "lane-changing" behavior by blinking the LED light strip on

Fig. 2: Constructed hallway environment with robot and participant in the early stage of hallway traversal.

Study Conditions			
		Passive Demonstration	
		No Demonstration	Demonstration
LED Signal	No LED	No Demonstration, No LED	Demonstration, No LED
	LED	No Demonstration, LED	Demonstration, LED

TABLE I: Study Conditions

the side of its chassis matching that of the direction of the lane that it intends to shift into. The robot can change lanes in order to avoid navigating into a path which conflicts with that of the person, however, the hallway is narrow enough that the person must also change into the opposing lane, in order to provide sufficient space for conflict-free passage. The first concept we explore in this study is the naturalness and efficacy of this signal in indicating the robot's intention.

The second concept is that of passively demonstrating the signal by having the robot use it in a context where the person can witness its usage without any explicit effort being made to gain the attention of the person, but prior to an interaction that necessitates understanding the signal's intent. This paradigm of establishing the meaning of the signal in advance of its necessity enables the person to be passively introduced to the signal's intention without requiring explicit, up-front training. The idea to introduce a passive demonstration to our interaction comes from a pilot study in which 13 participants (9 male, 4 female) reacted ambiguously to the LED signal; attempting to change lanes, but with some interpreting it as an instruction regarding which lane to shift into and others interpreting it as indicating the robot's intended path. In the study presented in this paper, the robot and the human traverse a 17.5 meter long corridor from opposite directions, passing each other along the way. To demonstrate its lane-changing behavior, the robot performs a lane-change in front of the user at the start of its path during this interaction.

These concepts are evaluated in a 2×2 user study, the conditions of which are described in Table I. On the first axis, the robot either does or does not employ LEDs to signal its lane-change behavior. On the second axis, the robot either does or does not perform a passive demonstration to the user prior to coming close enough to the user to force the robot to change lanes in order to avoid a conflict. The results of this study demonstrate only a modest improvement in reducing the number of navigational conflicts in the case of using LEDs in the lane-changing behavior, which becomes a very large improvement when the passive demonstration is introduced. This finding suggests that user understanding of non-anthropomorphic robotic signals can be significantly enhanced simply by allowing users to witness them being used in context.

II. Related Work

Light signals have long been used to communicate information across long distances and in limited visibility environments. Examples of such communication can be seen in aviation and maritime navigation [13]. Historically, the light signals used in these applications were usually very complex and required prior training to be understood, with one well-known example being Morse code [14]. Lights produced though bioluminescence also play part in the communication of some animals species (e.g., jellyfish, phytoplankton, fireflies, and pyrophorus) for purposes such as passive defense, baiting prey, or finding a mate [15]. A commonly-recognizable use of light signals in society is in the domain of automotive navigation. Light signals are used to alert drivers to the actions of others on the road in the form of brake lights and turn signals, in traffic lights to control the flow of traffic, and to alert drivers to emergencies. Additionally, they are commonly used to convey emergency information in buildings, such as with fire alarms.

Despite their abundance in society, research on the use of lights on robots for communication is still in its early stages by comparison to human-robot interaction involving humanoid robots and human-like behaviors [9]. Some current applications concentrate on expressing information such as subtle expressions [16] or simulated emotions [17] rather than directly communicating instructions or important state information. Others serve very basic functions which descend from consumer electronics, such as reporting the robot's battery status and or powered on state [9], [18].

Other research has explored how lights can be used to communicate a robot's internal state and functional intent [9]. Lights have been used to represent which actor is currently attempting to speak in a Human-Robot Interaction (HRI) dialogue task [19]. Animated lights have also been used to give aerial drone robots the ability to communicate navigational intent [20]. Autonomous motor vehicle applications for animated lights have also been explored to communicate the direction of turning and when it is safe to cross in front of the vehicle [21].

Most relevant to our work, Baraka et al. [18], [22] developed a framework for using animated lights for navigation tasks such as going from one location to another, as well as for human interaction tasks such as asking for human help. For navigation tasks, they use LEDs to indicate information such as the percentage that has been completed in an escort task, blockage by an obstacle, or whether the robot is turning left or right. However, a limitation of their experiments is that participants were asked if they could interpret the meaning of the lights in a video. In contrast, we examine how people interpret LED signals on a robot in the context of directly interacting with the robot when passing it in the opposite direction in a hallway.

III. Experimental Setup

The design of this system is based on two basic behaviors: a navigational behavior and a signaling behavior. The navigational behavior is intended to shift lanes, much as a car might in a roadway, in order to navigate around any person that it encounters who is also navigating the corridor. The signaling behavior is designed to indicate the robot's intention to shift lanes to human onlookers, allowing them to adjust their own behavior in order to minimize conflict. In addition to these two behaviors, the robot may perform a brief, passive demonstration of its lane-changing behavior, where no explicit effort is made to draw the participants' attention. This demonstration is accomplished by having the robot change lanes early in the interaction, at the opposite end of the corridor and at a distance that is sufficiently far from the person that the demonstration concludes entirely before the human is close enough for the robot to begin either its signaling or lane-changing behaviors.

To perform our experiment, a corridor was constructed from cubicle furniture in a large lab space, shown in Figure 2. A human study participant stands at one end of the corridor, with the robot positioned at the other end. The human and robot are both instructed to traverse the hallway to the opposite end. The corridor is 17.5 meters long and 1.85 meters wide, with cameras mounted at both ends, facing down the corridor, and a third camera mounted halfway down the corridor, facing the side that the study participant begins on. The width of a hallway is based on that of the hallways in our building and its length is constrained by that of our lab space. This setup is used in a 2×2 study, where two behaviors are varied. The robot either uses its LEDs when it turns or does not and either provides a brief passive demonstration of this behavior before coming into a range in which it may come into conflict with the human or does not.

A. Navigation

For the navigational behavior, the robot splits the hallway into three lanes, as one might divide a roadway. This formulation is diagrammed in Figure 3. The hallway itself is 17.5 meters long and 1.85 meters wide. Each lane is 0.65 meters wide, thus there is an overlap between the lanes. If the robot detects itself to be within 1 meter of a person who is also navigating the hallway, it will stop entirely in order to allow the person to safely pass. Thus, with the width of the hallway being 1.85 meters, it is necessary for the robot and the person to be in opposite lanes, outside of the middle lane, in order to pass each other without conflict.

Three distances are defined in our model of this problem, as can be seen in Figure 3. Distance d_{signal}, which is at 7 meters from the person, is the distance at which the robot will signal its intention to change lanes, and is based on the distance at which the robot can accurately detect a person in the hallway with its on-board sensors. The signal occurs on the side of the robot coinciding with the lane it intends to move into (Figure 4). Distance $d_{execute}$ is the distance at which the robot will execute its turn, at 2.75 meters from the person, chosen through testing as the last possible distance to execute a turn; where choosing the same lane will ensure that a conflict will occur and choosing opposite lanes will prevent a conflict. Distance $d_{conflict}$ is the distance at which the robot determines its motion to be in conflict with that of the person and comes to a complete stop, at 1 meter from the person; chosen empirically as the minimum possible distance required to stop safely.

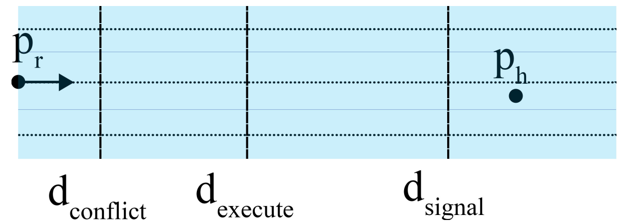
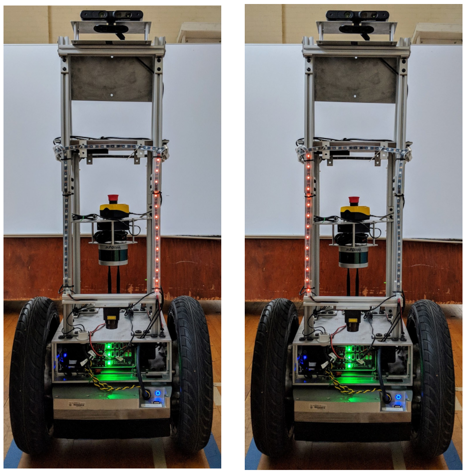


Fig. 3: A diagram of the corridor, its lanes, and the distance thresholds at which the robot signals its intention to change lanes, executes a lane change, and is determined to potentially be in conflict with a person in its path. The position of the robot is marked p_r. The respective action for each distance is executed as the position, p_h, of the person crosses these distance thresholds.

Because this study tests both the LEDs as a signal and the method of the passive demonstration for disambiguating this signal to the user, $d_{execute}$ is chosen to be the last possible distance that a person could choose to turn without coming into conflict with the robot. Naturally, $d_{execute}$ relies on a number of variables including the walking speed and reaction time of the person. This distance was chosen empirically - with the authors testing the system on themselves - but very effectively. The results demonstrate that when the robot does not signal its intention to turn, only turning when it arrives at this distance, that it comes into conflict with the person 100% of the time, as can be seen in Figure 5.

The navigational software is implemented as a custom Robot Operating System (ROS) [23] navigation stack which attempts to minimize the distance of a point 1 meter in front of the robot to the center of the desired lane while maintaining a constant linear velocity of 0.75 m/sec. Detecting the position of the person in the corridor with respect to the robot is accomplished with a classifier that detects the person's legs in the LiDAR scan data [24]. The system implements obstacle avoidance as a safeguard against possible navigational issues that could lead to a collision with a wall or the person during the course of the study, with distance ranges of $0 - 0.65$ meters for the wall and $0 - 1$ meters for the person, respectively.



(a) Left turn signal. (b) Right turn signal.

Fig. 4: Signal Animations for Directionality Intention.

B. LED Light Signal

The LED lights on the BWIbot consist of two 2 meter WS2812B strips with 60 LEDs each. This combination allows the strips to be attached to the beams on the front and rear of the robot, with strips on the left and right sides of the robot. Each LED can be individually controlled, and the array is controlled by an Adafruit Metro Mini 328 microcontroller. Though more complex signals are possible under this setup, the LEDs blink at a rate of 2 Hz (on 0.4 secs, off 0.1 secs) are colored yellow on the side that the robot will make its turn.[1], illustrated in Figure 4.

IV. Results

We recruited a total of 47 participants from The University of Texas at Austin community, 39 male, 8 female, ranging in age from 18 to 38 years. The data from 7 participants were discarded: 4 for failure to properly participate in the study (these participants stopped in front of the robot and attempted to test its capabilities or elicit responses from it), 3 due to software failures. The final pool of participants has 10 participants in each study condition.

After obtaining informed consent, participants were walked to one end of the corridor while the robot was set up at the opposite end. This was the participants' first encounter with the robot in the context of this study running the software stack presented in Section III, though the BWIBots roam the halls of UT Computer Science Department and the students recruited from the UT population may have observed them running a different software stack. Participants were instructed simply to walk to the opposite end of the corridor. As participants traversed the corridor, the robot did as well, creating the potential for a conflict as their paths crossed. After crossing the hallway once in this scenario, participants were administered a brief post-interaction survey comprising 35 8-point Likert and cognitive-differences scale questions describing the robot and the interaction. Overall, participation took between 10-15 minutes. The study is set up as a 2×2 between-participants design with 4 conditions as in Table I. Participants interacted with a robot which passively demonstrated a light change or did not, on one axis of this table; and which used an LED signal or did not, on the other. A video displaying examples of each of these conditions can be found at `https://youtu.be/T4CZcP8LKRM`.

[1]All code for the BWI project is hosted at `https://github.com/utexas-bwi` The LED-specific code is hosted in the segbot_led package `https://github.com/utexas-bwi/segbot/tree/master/segbot_led`

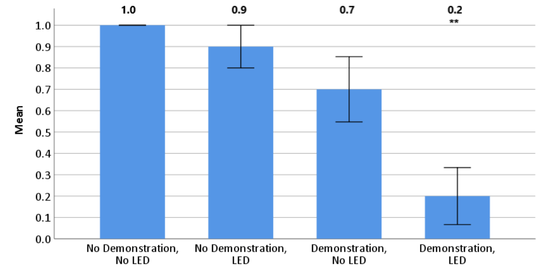


Fig. 5: Mean Conflict Across Study Conditions.

As a behavioral metric, we measure how often the robot and human study participant crossing each other's paths results in a conflict. Conflicts are defined as either the robot and the human coming to a complete stop because they come too close to one another without making a decision; the robot and the study participant entering into the same lane, forcing them to come to a stop; or scenarios in which the participant makes a rapid correction to attempt to avoid the robot, such as entering into the same lane as the robot and then changing lanes to the opposite lane, regardless of whether this causes either party to come to a stop. In the analysis of this study, conflicts were annotated based on video recorded during the interaction.

Our pilot study revealed a bias for participants to enter into the right lane (left lane from the perspective of the robot) in order to deconflict their path from that of the robot. Because the primary behavioral metric of this study is based on comparison of conflict scenarios, the study is designed to maximize the occurrence of these conflicts. As such, the robot always shifts into the left lane; where the participant is most likely to go by default. In addition to always going left, the robot makes its lane-change decision at the last possible moment, based on its distance from the person (2.75 meters, empirically tuned by the authors interacting with the robot). As a result, if the person has already chosen the same lane as the robot, it will almost surely result in a conflict. The purpose of this design is to maximize the impact of the intervention of introducing both the LED signal and the passive demonstration.

Results regarding the number of conflicting paths between the study participant and the robot are shown in Figure 5. A one-way ANOVA with an $\alpha = 0.05$ showed a significant main effect based on the the conditions of the study $(F(3, 36) = 9.913, p < 0.001)$. All pairwise post-hoc tests are based on Least Squares Difference (LSD), and are summarized in Table II.

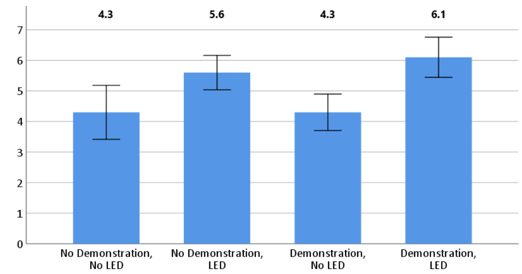
No Demo, No LED	No Demo, LED	$M = 0.1, p > 0.5$
No Demo, No LED	Demo, No LED	$M = 0.3, p = 0.07$
*** No Demo, No LED**	**Demo, LED**	$\boldsymbol{M = 0.8, p < 0.01}$
No Demo, LED	Demo, No LED	$M = 0.2, p = 0.22$
*** No Demo, LED**	**Demo, LED**	$\boldsymbol{M = 0.7, p < 0.01}$
*** Demo, No LED**	**Demo, LED**	$\boldsymbol{M = 0.5, p < 0.01}$

TABLE II: Pairwise Comparison with LSD Post-Hoc Test.

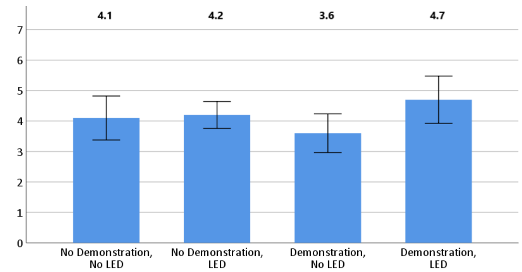
Results indicate almost no value to the use of the LED alone to signal the robot's turning behavior. Post-hoc tests showed no significant difference between showing the LED with no passive demonstration (the No Demonstration, LED condition) and simply not using the LED (No Demonstration, No LED), with only a modest mean difference ($M = 0.1, p > 0.5$). However, with the introduction of the passive demonstration technique we found that there is value in using the LED signals. Passively demonstrating the robot's lane-shifting behavior - having the robot perform a lane-shift in front of the participant further down the hallway, prior to their immediately proximal interaction with potential for conflict - is sufficient to reduce conflicts to a nearly-significant level (No Demonstration, No LED vs Demonstration, No LED: $M = 0.3, p = 0.07$). Moreover, when combined with the LED and despite the ineffectiveness of the LED signal on its own, this effect is compounded to a large margin at a significant level (No Demonstration, No LED vs Demonstration, LED: $M = 0.8, p < 0.01$). It can be seen that the compound effect of demonstrating the signal, rather than simply demonstrating the lane-shift, is what makes this effect so powerful (Demonstration, No LED vs Demonstration, LED: $M = 0.5, p < 0.01$).

The strength of the passive demonstration with the LED signal is further reflected in the results of the post-interaction survey, shown in Figure 6. None of the questions asked had a significant main effect, though here we present the responses for a few interesting questions. Participants appeared to interpret the robot's LED signal as an attempt to communicate (Figure 6a) and indicated that communication was most clear when the robot performed a passive demonstration alongside the LED signal (6b). The survey responses support the idea that the LED signal is not very useful on its own, while further reinforcing the value of the demonstration. Furthermore, a passive demonstration in the absence of a signal appears to have harmed performance on this metric, which may be reflective of participants noting a lack of communicative signaling during lane-shifting after witnessing the behavior twice with no communicative signal; despite the reduction in conflict in both passive demonstration conditions.

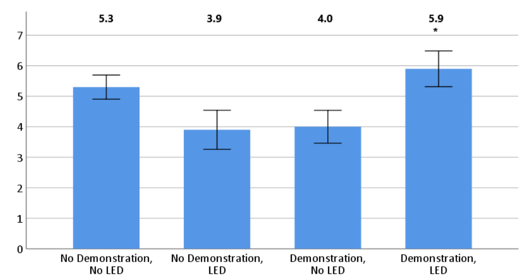
It is unsurprising that the interaction was found to be most comfortable in the presence of the passive training and the LED, Figure 6c, though the difference between "Do Demonstration, No LED" and "Demonstration, LED" is only quite small, with the worst performing conditions being "No Demonstration, LED" and "Demonstration, No LED." This result could either indicate that a larger sample size is necessary to clarify this response, or potentially that the LED



(a) "The robot was trying to communicate."



(b) "The robot communicated its intentions clearly."



(c) "The interaction was comfortable."

Fig. 6: Responses to Likert-scale questions from the post-interaction survey.

or demonstration on their own are simply confusing to participants. This also points toward a potentially-confounding variable and limitation in the design of this study, which is that the overall path of the robot in the conditions in which it provides a passive demonstration is curvier, as it must make two lane-changes instead of one in order to provide the demonstration. Eliminating this issue will require observing this behavior in additional scenarios so as to determine the magnitude of the overall effect of the curviness of the path. This may, indeed, be reflected in our survey results for the questions, "The robot communicated its intentions clearly" (Figure 6b) and "The interaction was comfortable" (Figure 6c).

V. Conclusion

It is interesting that a signal as familiar as the turn signal on a car would become difficult to interpret when divorced from the context of driving. Our initial assumption on crafting the pilot study was that users would find turn signals on a robot to be entirely intuitive, and that the experience that they had gained from driving - which involves navigating a space shared with other cars - would directly transfer to the task of navigating a space shared with a robot. This was not the case. Instead, our study revealed that simple passive demonstrations of the signal to study participants were sufficient to disambiguate the intention of this signal to them.

These findings leave open, however, the question as to whether this method would easily extend to other novel signals. Is it that the robot's demonstration, combined with the familiarity of turn signals, gives rise to our result; or that this technique would extend to entirely novel signals that are not encountered in day-to-day life? Probing this question will require the design of studies which use non-anthropomorphic signals in scenarios that are not commonly encountered outside of interactions with robots, such as collaborative manipulation tasks. We hope to further explore this question in experiments with newer versions of the BWIBot which incorporate robotic arms.

This result will inform the design of future versions of our BWIBot's navigation stack, whereby we intend to add turn signals to the robot, but also to program the robot to perform a few quick lane-shift and turning maneuvers in front of unfamiliar faces; thus enabling new users to acclimate to the behavior of the system. Once complete, we will perform studies of the system involving larger crowds and longitudinal studies of the deployed system on the BWIBot platform. These studies are currently in the planning phases. As it stands, our result demonstrates a scenario win which passive demonstrations are able to provide the context required to interpret the robot's LED signal to users, and opens the study of such passive demonstrations an interesting new direction for further research.

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