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Expressive Lights for Revealing Mobile Service Robot State

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Abstract

Autonomous mobile service robots move in our buildings, carrying out different tasks and traversing multiple floors. While moving and performing their tasks, these robots find themselves in a variety of states. Although speech is often used for communicating the robot's state to humans, such communication can often be ineffective, due to the transient nature of speech. In this paper, we investigate the use of lights as a persistent visualization of the robot's state in relation to both tasks and environmental factors. Programmable lights offer a large degree of choices in terms of animation pattern, color and speed. We present this space of choices and introduce different animation profiles that we consider to animate a set of programmable lights on the robot. We conduct experiments to query about suitable animations for three representative scenarios of an autonomous symbiotic service robot, CoBot. Our work enables CoBot to make its states persistently visible to the humans it interacts with.

Introduction

Collaborative service robots are meant, through symbiotic autonomy (Veloso et al. 2012a), to effectively collaborate with humans in order to successfully perform their tasks. With symbiotic autonomy, a two-way symmetric relationship holds: the robot servicing the human and the human servicing the robot. While our own collaborative robots, the CoBots (Veloso et al. 2012b), move in our buildings, successfully carrying out different tasks and traversing multiple floors, there is a need for revealing their internal states in several situations where they are meant to collaborate with humans. Currently, our CoBots communicate mainly verbally. They speak instructions out to both task solicitors (people who request tasks from the robot) and task helpers (the human actors in the symbiotic autonomy process). However, these mobile robots have many features in their internal state, including map representations, task and sensor information, which are all not visible to humans. One of our important goals is to find a good way of expressing information and internal state of our CoBot robots through visible features to humans. For this purpose, verbal communication has its limits. One of them is proximity: on-robot verbal communication is limited to the intimate, personal and social domains (Bethel 2009). There are some cases where communication in the public domain is required (especially when the robot is calling for help), and verbal communication (or even on-screen display) are helpless in this case. Another limitation of verbal communication is its transient nature (the expression lasts the duration of a sentence).

To remedy these problems, we propose to use lights as a medium of communication from robot to humans, as a way to reveal to them the internal state of the robot. Unlike however most of the existing robots that use lights for expression of state, CoBot is a mobile robot that interacts with humans in different specific manners: requests help (to activate objects in its tasks), influences change in the user's motion (in relation to its own motion) or provides useful information (task-related or general). The spectrum of entities potentially expressed through these lights is hence greatly diverse and non-simplistic.

The rest of the paper is organized as follows. Section II discusses related work. Section III describes the design of our light interface for revealing the internal state of the robot. In section IV, we focus on three scenarios CoBot finds itself in and investigate the *what* and *how* of the expression of internal state. Finally, Section V shows experimentation and results obtained in the quest for appropriate light animations for these scenarios.

Related Work

Most human-oriented technology generally makes use of some form of light indicators. Lights are used in personal electronic devices ranging from cell phones to toasters, and their expressivity can be greatly exploited (Harrison et al. 2012). Expressive lights have also been used in wearable technology (on apparel for instance (Choi et al. 2007)) and interactive art installations (Holmes 2013) (Betella et al. 2013). Another important but different use of light is for stage or scene lighting, which still shares common expressive features with indicator lights like color, intensity and time-varying patterns (De Melo and Paiva 2007). As robots themselves become more human-oriented, designers and researchers started integrating lights on robots (like has been done with the NAO or the AIBO robots) for non-verbal com-

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munication. More recent works have considered more advanced use of lights specifically on robots, which we describe next.

The purpose of using lights on robots varies in the different works we found, but almost all uses of expressive lights on robots still remain rudimentary. First, the work of Kobayashi et al., the aim is to make impressions on the user rather than explicitly try express something tangible. The type of expressions used in this work are called artificial subtle expressions (ASE's) and are not linked to an internal state the robot finds itself in (Kobayashi et al. 2011). Second, explicit expression of emotions in robots and artificial agents has recently become an active area of research in the field of affective computing (Castellano et al. 2013). For instance Rea, Young, and Irani use lights on a robot to express people's emotions in a cafe-style room (Rea, Young, and Irani 2012). Another example of affective expression through lights is the use of lights as a complement to facial expressions (Kim et al. 2008). Third, lights can sometimes be used for functional purposes. Examples include debugging or improving human-robot interaction in a practical way like the work done by Funakoshi et al., where a blinking LED is used to avoid utterance collisions in verbal human-robot communication (Funakoshi et al. 2008). Finally, lights can be used to communicate intent, such as flight intent of an aerial robot (Szafir, Mutlu, and Fong 2015).

Most of the works presented above mainly focus on the "what" component of expression (what to express). Equally important to that is the "how" component (how to express). Harrison et al. presented in-depth analysis and study of possible ways of using a single point light source to express a wide array of messages (Harrison et al. 2012). This work is a good starting point for thinking of ways to use a set of lights as a genuinely expressive and functional medium.

Light Interface for State Revealing

Formalization

Robot internal state We assume that the *full* state of the robot at a particular time can be represented as the tuple:

$$\mathcal{S}(t) = \langle \mathcal{F}(t), \mathcal{P}(t) \rangle$$

where:
- $\mathcal{F}(t) = (f_1(t), ..., f_n(t))$ is a vector of (discrete) state *features* that determine the type of state the robot is in.
- $\mathcal{P}(t) = (p_1(t), ..., p_n(t))$ is a vector of (possibly continuous) state *parameters* which modulate the state within the state type defined by $\mathcal{F}$. The reason why we distinguish between features and parameters is that we would like to associate a light animation type to a state type (determined solely by feature variables), but we would also like to modulate this animation with possibly varying parameters without having to define microstates for each parameter value. Both feature and parameter variables are functions of sensor and/or task execution information. Some parameters might be relevant to one or more state types, and irrelevant to others, depending on the value of $\mathcal{F}(t)$.

From $\mathcal{S}(t)$, we are only interested in $\mathcal{S}'(t) \subset \mathcal{S}(t)$, which we call the *relevant* state. It represents the set of variables we wish to make transparent to the outside world, or externalize. We write $\mathcal{S}'(t)$ as: $\mathcal{S}'(t) = \langle \mathcal{F}'(t), \mathcal{P}'(t) \rangle$ where $\mathcal{F}'(t)$ and $\mathcal{P}'(t)$ are the *relevant* state features and parameters, respectively. The optimal choice of $\mathcal{S}'(t)$ from $\mathcal{S}(t)$ is a separate research question that is beyond the scope of this paper. To each state in the relevant state space, we would like to associate an animation of the lights. We are looking for a mapping $\mathcal{M} : \mathcal{S}' \to \mathcal{A}$, where $\mathcal{A}$ is the set of possible animations that we consider. Next, we define our framework for light animations.

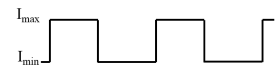
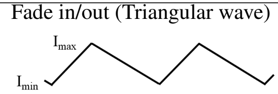
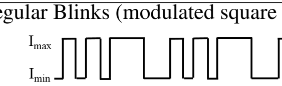
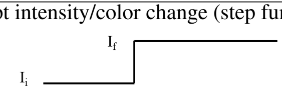
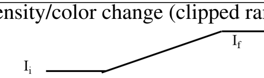
Light animations An animation A of a set of n lights is defined as a time-varying n-by-3 matrix of light intensities:

$$A(t) = \begin{pmatrix} i_{1R}(t) & i_{1G}(t) & i_{1B}(t) \\ i_{2R}(t) & i_{2G}(t) & i_{2B}(t) \\ \vdots & \vdots & \vdots \\ i_{nR}(t) & i_{nG}(t) & i_{nB}(t) \end{pmatrix}$$

where the rows represent the indices of the individual lights (which we call pixels from now on) and the columns represent the R, G and B components of each pixel.

Similar to (Harrison et al. 2012), we focus on a limited set of possible intensity functions $i_{jk}(t)$. The functions we consider are summarized in Table 1.

Table 1: Shapes considered for each $i_{jk}(t)$

Periodic	Blink (square wave) 
	Fade in/out (Triangular wave) 
	Irregular Blinks (modulated square wave) 
Non-periodic	Abrupt intensity/color change (step function) 
	Slow intensity/color change (clipped ramp function) 

For each animation A, we restrict ourselves to the case where all $i_{jk}(t)$'s in $A(t)$ have the same shape among the ones presented in table 1. We also allow a possible offset between the rows of $A(t)$ if we want to achieve a scan over the lights in space, depending on the pixel's spatial configuration. Note that if the ratios $I_{R,max} : I_{G,max} : I_{B,max}$ and $I_{R,min} : I_{G,min} : I_{B,min}$ are maintained in these animations, it will result in a monochromatic animation. If the ratio is not respected however, we see changes in color throughout the animation.

Proposed interface

Figure 1 shows all parts of the proposed interface. A node running on the robot itself (1) collects state information

$\mathcal{S}'(t)$ at every time step. Any change in $\mathcal{S}'(t)$ will trigger a command from (1) to the microcontroller (2), notifying it only of the variables in $\mathcal{S}'(t)$ which changed. The microcontroller keeps track of $\mathcal{S}'(t)$ locally (in synchronization with (1)'s copy of it). Also, although state variables are constantly updated, only data variables which are relevant to the current state are updated. (2) acknowledges that it correctly received the command by responding to (1) with an

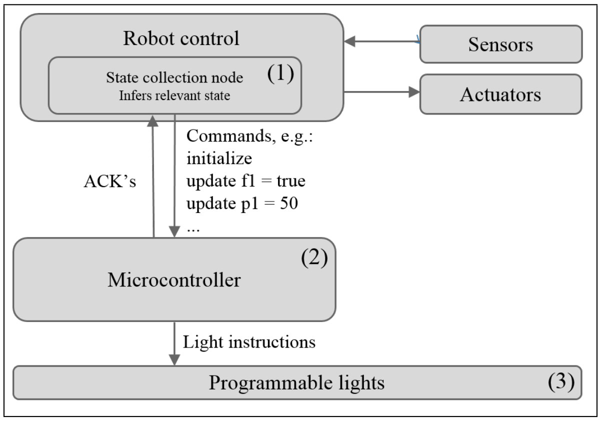


Figure 1: Control diagram of the proposed programmable lights interface

acknowledgement (ACK in the figure). (2) is programmed with the state-animation mapping $\mathcal{M}$ mentioned in the previous section, and triggers the animation $\mathcal{M}(\mathcal{S}'(.))$ in the programmable lights (3) at each state change. The animation then runs continuously until interrupted by a subsequent state change.

We implemented the interface described above on our collaborative mobile service robot, CoBot, which runs the ROS operating system. The state collection node is a simple ROS node that subscribes to different topics published by other nodes which provide enough information to infer $\mathcal{S}'(t)$ at every time step. An Arduino Uno board was used as the microcontroller, communicating serially with both (1) and (3) in Figure 1. The program on the microcontroller alternates between a cycle in which it listens to possible updates and a cycle in which it refreshes (3) (it cannot perform both simultaneously). For the programmable lights, the Adafruit NeoPixels strip, a linear LED strip with individually controllable pixels, was chosen. Compared to other options like luminous fabrics or LED panels, a linear strip is both simple in structure and flexible to adopt different mounting alternatives on CoBot. The NeoPixels strip moreover provides high light intensity thanks to its density of 144 LEDs/m (35 Watts/m max). It was mounted vertically over the body of the CoBot as shown in the hardware diagram of Figure 2.

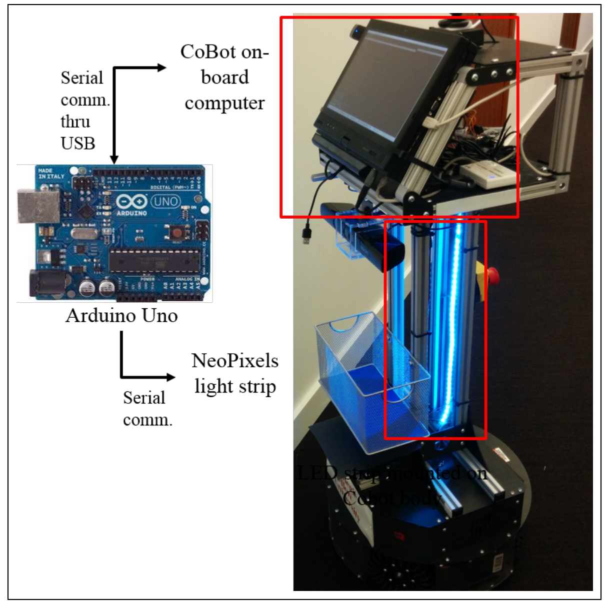


Figure 2: Hardware interface design

In practice, the limited medium we are dealing with (a single strip of lights) gives rise to a tradeoff between legibility of expression and diversity of the vocabulary of the interface. From the robot's perspective, this can be seen as a tradeoff between transparency of the robot's internal state (*what* it reveals) and understandability of the elements it externalizes (*how* well it reveals it). As a consequence, choosing *what* to express is an important step before thinking of *how* to express. The choice of states that will require animation are directly coupled to the possible impact the addition of lights could make in these states, in relation to the tasks carried by the robot and their associated needs. In this paper, we focus on three situations that we believe are representative of the situations a mobile service robot like CoBot generally finds itself in while performing its diverse tasks.

Opportunistic Cases for Light Expression: What and How to Express?

There is a wide spectrum of aspects of the robot's internal state and needs that could be expressed through lights (virtually any set of variables belonging to full state of the robot).

Selected scenarios

Waiting for human input (Scenario "waiting") CoBot is a symbiotic autonomous robot (Veloso et al. 2012a) that proactively asks for help given its limitations. It often finds itself in situations where it is waiting for a human input to carry on its tasks. For example, as it does not have arms, it cannot press the elevator buttons when it wants to travel from floor to floor. It then needs to ask for help and says "Please press the button of the elevator", when it is in the elevator hall. Such spoken request is not always very effective, because of the transient nature of the communication (intermittent repetition of the phrase) and the limited auditory range. The presence of lights, which can be seen at all times and that are bright enough to be seen from far away, might provide a more effective way of expressing CoBot's need for help from passing-by humans.

Blocked by a human obstacle (Scenario "blocked") CoBot's navigation is often impeded by humans who stand in its way. In these situations, and as CoBot does not deviate more than a predefined threshold from its planned route, it will not be able to move unless the person moves out of its way. CoBot issues a verbal request "Please excuse me" with the hope that the human opens a path for it to pass. Again, the verbal command could be complemented with lights as a more effective way to express the robot's need for the obstacle to move so that it can resume its execution.

Showing task progress to a user (Scenario "progress") This is a scenario where there is a need to display the progress of the robot on a task (for example, CoBot escorting a visitor to a room). The presence of a progress indicator has been shown to reduce user anxiety (Myers 1985). In the escort example , as the visitor follows the robot and does not know the location of the destination room, he/she is ignorant of how much is left to navigate. We investigate the use of lights to display progress, as a function of the estimated distance from the task goal.

Relevant state choice

Considering only the three scenarios described above, the relevant state $\mathcal{S}'$ is represented by the following set of state variables (both features and parameters).
The relevant feature variables $\mathcal{F}'$ are:
- `path_blocked` (abbr. `pb`): a boolean variable indicating whether CoBot's path is impeded,
- `el_waiting` (abbr. `ew`): a boolean variable indicating whether the robot is waiting for human input at an elevator
- `task_type` (abbr. `tt`) : a variable indicating the type of task being executed. We are interested in the value `esc`, which indicates that a person is currently being escorted.
The relevant parameters $\mathcal{P}'$ used are `esc_tot_time` (abbr. `et`) and `esc_rem_time` (abbr. `er`) which indicate respectively the estimated total and remaining time for the current escort task.
The state values associated with each of the three scenarios are summarized in Table 2. ($\times$ represents a "don't-care")

Table 2: Mapping from scenario to state for the scenarios considered

Scenario	pb	ew	tt	et	er
"waiting"	0	1	×	×	×
"blocked"	1	×	×	×	×
"progress"	0	0	esc	variable	variable

Animation framework

Parametrization of $\mathcal{A}$ To simplify the search for suitable animations for each of the scenarios presented above, it is useful to focus on a finite set of parameters that fully define the animation. Finding suitable animations will hence reduce to finding suitable values for these parameters.

We used a different parametrization for scenarios "waiting" and "blocked" than we did in scenario "progress", given that the nature of the expression differs considerably. The parametrization used for the different scenarios are described next.

– Scenarios "waiting" and "blocked": For these scenarios, we opt for a periodic animation function. Furthermore, all pixels have identical animations, i.e. all rows of $A(t)$ are equal functions of time. The parameters we look at are the following: the animation function shape wv (selected from the possible options shown in Table 1), the dynamics parameter D (defined as the percentage of the period where the function is high or rising), the period T and the R:G:B ratio or color (R, G, B). The maximum intensity $I_{max} = I_{R,max} + I_{G,max} + I_{B,max}$ is set to a constant and I_{min} is set to be zero for R,G and B.

– Scenario "progress": For this scenario, we consider non-periodic animation functions and do not require the animation functions of all pixels to be synchronized. We look at the following parameters: progress display method $disp$ (how is the progress towards the goal expressed?), direction of progress displayed u_{disp} (only if the progress is displayed spatially in the form of a progress bar for instance), the initial color $(R, G, B)_i$ (color of the strip at the beginning of the escort) and the final color $(R, G, B)_f$ (color of the strip when the goal is reached).

Animation algorithms As discussed in previous sections, there is a direct mapping between $\mathcal{F}'$ and $\mathcal{A}^*$, where $\mathcal{A}^*$ is the parameterized set of animations we consider. The following animation functions are triggered by values taken by the vector $\mathcal{F}'$:

- `anim_waiting(`wv, D, T, R, G, B`)`
- `anim_blocked(`wv, D, T, R, G, B`)`
- `anim_progress(`$disp, u_{disp}, (R, G, B)_i, (R, G, B)_f$`, et,er)`

Note that `et` and `er` are the state parameters $\mathcal{P}'$ which modulate the corresponding function `anim_progress`, while the rest of the function arguments are all design parameters (to be determined in the next section). The first two functions, linked to a periodic animation as mentioned above, only execute one period of the animation. The last function only performs an update to the light strip depending on the state parameter values. Putting these in a loop structure performs the required animation, as shown in Algorithm 1. Note that the scenarios can overlap (for example being blocked or reaching an elevator while escorting), so we need prioritization of these scenarios.

Algorithm 1 Animation control algorithm

```
while true do
    (F', P') = UPDATE_STATE()
    if pb == 1 then anim_blocked(wv,D,T,R,G,B)
    else
        if ew == 1 then anim_waiting(wv,D,T,R,G,B)
        else
            if tt == "esc" then anim_progress(...,et,er)
```

Study: Animation Selection

Methodology: In order to select suitable parameters for the animations presented above, we conducted a study with a video-based survey. Participants were first given detailed description about the situation of the robot in each scenario and then asked to watch videos showing the robot in each of the scenarios defined above, while answering a survey through the form of a spreadsheet.

Preliminary Study: A preliminary study was conducted with the people who have the most expertise for our purposes, namely the developers of CoBot. 8 CoBot developers participated in the survey, and submitted their choices. To validate our design choices, we recruited 30 more people to include in the study. The results across both studies were consistent. The extended study is described next.

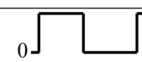
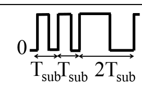
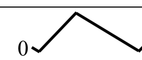
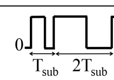
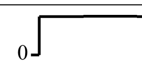
Participants: A total of 38 participants took part in this study. 61% study or work in a robotics-related field, 18% are in a design-related field and 21% are in an engineering-related field. Ages range from 19 to 50 years with an average of around 25 years. 18% are from North America, 32% are from Europe, 29% are from the Middle East and 21% are from Asia. 68% are male and 32% are female.

Survey design: Participants were asked to give their input on three aspects of the animation: first, the animation type, then the preferred speed on the animation they selected and finally the color of the lights. For each scenario, 3 different types of animations where shown with the same color (light blue). Nuances of three different speeds were also shown within each type. The participants were asked to select the one that they thought would fit best the robot's expression purposes in the given scenario. Participants were also shown 6 possible light colors in the form of a static image of the robot with its lights on. They were also asked to select the most appropriate color for each scenario. For simplicity, we assumed that the choice of color for the animation is independent of the actual animation selected, which helped reduce the amount of choices to be shown. This is not an unreasonable assumption to make : while animation type (or pattern) and speed both relate to modulations in time and intensity, color seems to be much less intertwined to the other two. Furthermore, according to color theory (Wright 2009), color on its own plays a strong role in expression (especially when expressing emotions or moods).
Next we list and justify the choices of animation types presented to the participants.

- Scenario "waiting": A regular blinking animation (Blink); a siren-like pattern; a rhythmic (non-regular) blinking animation. We believe these to be good candidates for grabbing attention because of the dynamic aspect, the warning connotation and the non-regular pattern respectively.
- Scenario "blocked": A faded animation (that we call "Push") that turns on quickly and dies out slower (giving the impression of successively pushing against an obstacle); an "aggressive" blink (fast blink followed by slow blink); a simple color change at the time the robot gets blocked. We believe these to be good candidates for inciting the human to move away from the path.
- Scenario "progress": A bottom-up progress bar where lights gradually fill from top to bottom proportionally to the distance from the goal; a top-down progress bar where lights fill from the top towards the bottom; a gradual change from an initial color to a final color, again proportionally to the distance from goal.

The parameter values associated with the animations described above are summarized in Table 3. In addition to the animation summarized in the table, the following colors were shown for each scenario as static images of the lighted robot: Red (R), Orange (O), Green (G), Light Blue (B), Dark Blue (B') and Purple (P).

Table 3: Parameter values for the animation choices shown

Scenario	wv	D	T (s)
"waiting"	Blink		
		0.5	2/1.6/0.6
	Siren		
		0.5	2/1.6/0.6
	Rhythmic Blink		
		0.5	3/2.5/1.5
"blocked"	Push		
		0.25	1.5/1/0.5
	Aggressive Blink		
		0.5	2/1.6/0.6
	Color change		
		1	-
"progress"	$disp$	u_{disp}	
	prog_bar	bottom_up	
	prog_bar	top_down	
	color_change	-	

Results

Table 4 shows the selected best choices, which were consistent between the preliminary and the extended study. Figure 3 and Table 5 show the distribution of the results in the extended study. In the following discussion, the p-values mentioned are obtained from a Chi-Square goodness-of-fit test against a uniform distribution.
In Figure 3, we show the results for the animation type. For the scenario "waiting" (p-value of 0.0137), among the

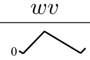
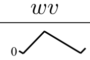
participants who chose the winning animation ”Siren”, 64% chose the slower speed, 29% the medium speed and 7% the faster speed. For the scenario ”blocked” (p-value of 0.0916), among the participants who chose the winning animation ”Push”, 27% chose the slower speed, 40% the medium speed and 33% the faster speed. For the scenario ”progress” (p-value of 1.10^{-6}), the participants chose the bottom-up progress bar animation. All p-values obtained are below 0.10, which indicates a strongly non-uniform distribution of preferences for each scenario, and this can clearly be seen in Figure 3.

The results for colors (Table 5) similarly show a clear preference for one option in each case. For instance, light blue was selected for the ”waiting” scenario. This result supports the statement in (Choi et al. 2007) that cold colors are better than warm colors at grabbing attention. Also, red was selected as the best color for the ”blocked” scenario. This is consistent with the fact that red is often perceived as demanding (Wright 2009) or stimulating (Choi et al. 2007), which are both desirable in this scenario.

The results of the study show that some design alternatives for the animations can be completely eliminated, while a small set can be considered valid. Although there is generally a clear preference for one of the choices in each scenario, this study was informative of the distribution of preferences, which gives us the tools to possibly generate animations according to some probability distribution instead of only committing to a single one.

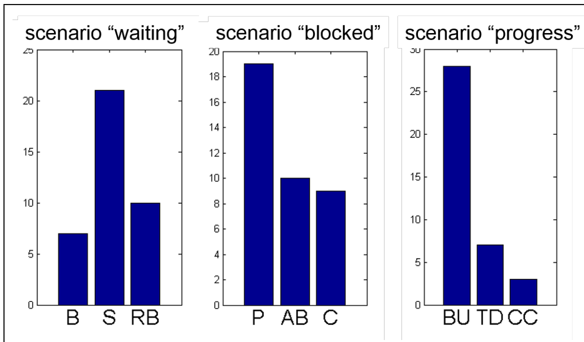
The scenarios we looked at are quite generic and can be commonly encountered in other situations involving a social robot and a human. However, before extrapolating our results to other platforms, we need to make sure that other factors (e.g. light strip shape, size or placement, robot appearance, light diffusion mechanism ...) do not influence the perception of the expression. These results can still however serve as a starting point for the design of future social robotics system which use lights as a mean of communication.

Table 4: Selected best animations for each scenario

Scenario	Animation and parameters			
”waiting”	Light blue ”Siren” with period 2s			
	wv	D	T (s)	Color
		0.5	2	Light Blue
”blocked”	Red ”Push” with period 1.5s			
	wv	D	T (s)	Color
		0.25	1.5	Red
”progress”	Bottom-up progress bar			
	$disp$	u_{disp}	In. Color	Fin. Color
	prog_bar	bottom_up	Red	Green

Conclusion and Future Work

We have proposed a design for an interface between a collaborative mobile robot and programmable lights to be used for expressively revealing the robot’s internal state. We have focused on three scenarios where our collaborative robot, CoBot, finds itself in and could use the help of lights for expressing parts if its internal state. Finally, we presented a study to select appropriate parameters for the light animations in each of the three scenarios we consider.



B=Blink; S=Siren; RB=Rhythmic Blink;
P=Push; AB=Aggressive Blink; C=Color;
BU=Bottom-up; TD=Top-down; CC=Color Change

Figure 3: Animation type results

Table 5: Color results

Scenario	Color					
”waiting”	R	O	G	B	B’	P
	13%	13%	13%	39%	16%	6%
”blocked”	R	O	G	B	B’	P
	53%	29%	5%	0%	10%	3%
”progress” (top 6 choices)	R/G	B/P	B’/G	O/G	O/B	P/B
	27%	12%	12%	8%	8%	8%

Our ultimate future goal of using expressive lights on a mobile service robot is threefold. It can be summarized by the three I’s: Inform, Influence and Interact. Firstly, Informing consists in having some transparency to the robot’s internal state. Secondly, Influencing consists in changing human behavior to the robot’s advantage. Thirdly, Interacting possibly includes an affective component of communication. In the current paper, although we have superficially touched at all three points mentioned above, the evaluation was mainly relevant to the first component. It would be interesting as a next step to evaluate the second component, i.e. to what extent our lights can influence or change human behavior.

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