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# Motion Overlap for a Mobile Robot to Express its Mind

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**This paper discusses how a mobile robot may express itself to get help from users in a cooperative task. We focus on a situation in which a robot expresses its state of mind to get a user to lend it help. The design we propose, called *motion overlap* (MO), enables a robot to express human-like behavior in communicating with users. We reasoned that human-like behavior in a robot could help the user to understand its state of mind. We designed a small sweeping robot based on MO that conducts *back and forth movement*, and compared its MO expression in experiments with other nonverbal communication, i.e., buzzers and blinking LEDs. We found that the MO expression encouraged most users to help the robot. Differences among results obtained for the three types of expression were statistically significant, and results demonstrate that MO has potential in the design of robots for the home.**

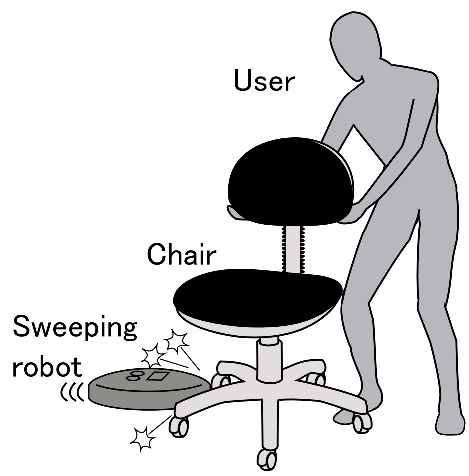


**Fig. 1.** Robot needing a user's help.

**Keywords:** interaction design, sweeping robot, robot mind, motion design, nonverbal communication

## 1. Introduction

Robots for the home, including sweeping robots and pets, have been commercialized and now are being studied for use in cooperative housework [10]. In cooperative housework, home robots must ask users for help if they encounter difficulties that they cannot overcome themselves, e.g., a sweeping robot unable to move a heavy obstacle such as a chair or a table preventing from doing its job must ask a user to remove the obstacle (**Fig. 1**). The problem is how to enable the robot to communicate its requests to the user in cooperative work.

Some studies have proposed design for electric home appliances. Norman [18] addressed the use of affordance [5] in artifact design. Suchman [25] studied behavior patterns of users. Users' reaction to computers [8, 21] is important to consider when designing artifacts. Yamauchi et al. studied function imagery of auditory signals [28], and Japanese Industrial Standards include guidelines for auditory signals in consumer products for elderly people [7]. These studies and guidelines deal with interfaces for artifacts that users operate directly themselves. These methods and guidelines assume use of an artifact directly through user control – an approach that may not necessarily work well for home robots that conduct tasks directly themselves. Robot-oriented design approaches are thus needed for home robots.

Our proposal for having a mobile robot express itself assumes cooperative work in which the robot must make users aware of how to operate it and move objects blocking its operation – a trinomial relationship among the user, robot, and object. The theory of mind (TOM) [1] deals with such trinomial relationships. Following TOM, we term a robot's internal state "mind," defined as its own motives, intents, or purposes and goals of behavior. We take the weak AI [22] position: robots can be made to act as if they had a mind.

Mental expression is designed verbally or nonverbally. If we use verbal expression, for example, we have the robot speak, saying, "Please help me by moving this obstacle." In certain situations, the robot may simply repeat such speech because it cannot recognize the status of its environment. Speech conveys a unique meaning, and such repetition may irritate users. We thus chose to study nonverbal methods such as buzzers, blinking lights, and movement, which convey ambiguous information that users can interpret as they like based on the given situation.

We consider that the motion-based approach feasibly and effectively conveys the robot's mind in an obstacle-removal task. Movement is designed based on *motion overlap* (MO) that enable the robot to move in a way that the user narrows down possible responses and acts appropriately. In the obstacle-removal task, we had the robot move *back and forth* in front of an obstacle, and conducted experiments compared MO to other nonverbal approaches. Experimental results showed that MO has potential in the design of robots for the home.

## 2. Related Work

We assume that the mobile robot is cylindrical and expresses itself through movement. This has advantages for developers in that the robot needs no components such as displays or speech synthesizer, but it is difficult for the robot to express itself in a humanly understandable manner. Below, we give an overview of studies on how a robot can express itself nonverbally based on whether the robot is human-like or nonhuman-like in shape.

### 2.1. Expression with Human-Like Shape

Hadaly-2 [6], Nakata's dancing robot [16], Kobayashi's face robot [9], the document-delivery robot CREO [23], Breazeal's Kismet [2], Kozima's Infanoid [12], Robovie-III [14], and Cog [3] are examples of human-like robots that easily express themselves nonverbally in a humanly understandable manner. The robot we are interested in, however, is nonhuman-like in shape, only having wheels for travel. We designed wheel movement to enable the robot to express its mind.

### 2.2. Expression with Nonhuman-Like Shape

Ono et al. [20] studied how a mobile robot's familiarity influenced a user's ability to understand what was on its mind. Before their experiment, participants were asked to "grow" a life-like agent on a PC, after which it was moved to the robot's display. Matsumaru et al. [13] developed a mobile robot that expresses its direction of movement with a laser pointer or animated eye. Komatsu [11] reported that users could infer the attitude of a machine through its beeps. Those require extra components, unlike our proposal. The orca-like robot [17], seal-like Paro [24, 27], and limbless Muu [19] are efforts of familiarizing users with robots. Our study differs from these, however, in that we assume actual cooperative work between the user and robot, such as sweeping.

## 3. Robot Mind Expression

The obstacle-removal task in which we have the robot express itself in front of an obstacle and how the robot conveys what is on its mind are explained below.

### 3.1. Obstacle-Removal Task

The situation involves a sweeping robot unable to remove an obstacle such as a chair that asks a user to remove the chair so that it can sweep the floor where the obstacle was (**Fig. 1**). Such an obstacle-removal task serves as a general testbed for our work because it occurs often in cooperative tasks between users and robots. To execute this task, the robot must communicate its problem to the user and ask for help. This task has been used in research on cooperative sweeping [10].

Obstacle-removal tasks generally accompany other robot tasks. Obstacle avoidance is essential to mobile robots such as tour guides [4]. Obstacles may be avoided by having the robot (1) avoid an obstacle autonomously, (2) remove the obstacle autonomously, or (3) get user to remove the obstacle. It is difficult for a robot to remove an obstacle autonomously because it first must decide whether it may touch the object. In practical situations, the robot avoids an obstacle either by autonomous avoidance or having a user remove it.

### 3.2. Motion Overlap

Our design, *motion overlap* (MO), starts when movement routinely done by a user is programmed into a robot. A user observing the robot's movement will find an analogy to human action and easily interprets the state of mind. The overlap between user and robot movement causes an overlap between the minds of the user and the robot (**Fig. 2**).

Human beings are not natural light emitters nor do they convey intent easily using nonverbal sounds. They do, however, move expressively when executing tasks. We therefore presume that a user can understand a robot's mind as naturally as another person's mind if robot movement overlaps recognizable human movement.

As stated above, nonverbal communication has alternative modalities: a robot can make a struggling movement, sound a buzzer, or blink a light. We assume movement to be better for the obstacle-removal task for the following reasons.

- *Feasibility*: A robot must move as it executes tasks, so a motion-based approach requires no additional components such as LEDs or speakers that other nonverbal approaches would require, making them more expensive.
- *Variety*: The motion-based approach enables us to design informational movement to suit different tasks. The variety of movements possible is far larger than the variety of sounds or light signals of other nonverbal methods.
- *Stress minimization*: Other nonverbal methods, particularly sound, may force a user to direct attention specifically at the robot, causing more stress than movement would. The motion-based approach

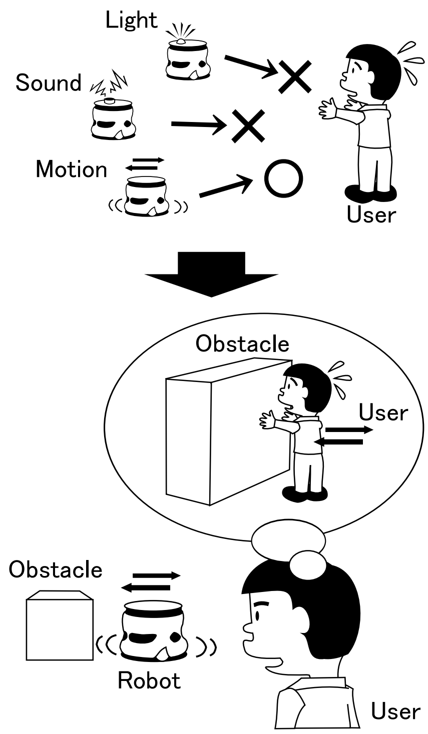


**Fig. 2.** Motion overlap.

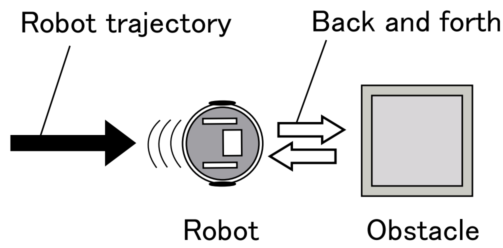


**Fig. 3.** back and forth movement.

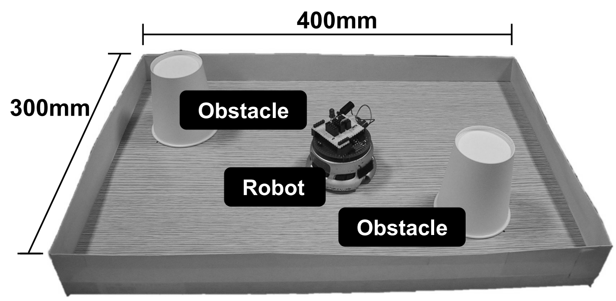


**Fig. 4.** Experimental environment.

avoids distracting or invasive interruption of a user who notices the movement and chooses whether or not to respond.

- *Effectiveness*: Motion-based information is intuitively more effective than other nonverbal approaches because interesting movement attracts a user to a robot without stress.

While feasibility, variety, and stress minimization in motion-based information may appear intuitively valid, however, effectiveness must be verified experimentally.

### 3.3. Application of MO to Mobile Robot

We designed the robot's movement easily understood by users considering what human beings might do when faced with the obstacle-removal task. Take a person whose hands are full of baggage hesitating nervously in front of a closed door. Most human observers would identify the problem immediately. Using similar hesitation could enable the robot to inform the user that it needs help. Here again, however, implementation of such behavior depends in part on the robot's shape, i.e., whether it is human-like or not.

A study on human actions in doing tasks [26] defines hesitation as movement that suddenly stops and either changes into other movement or is suspended – a definition that our *back and forth movement* fits (**Fig. 3**). Seeing a robot move back and forward in a short time in front of an obstacle should be easy for users because human beings act similarly when they are in trouble.

We could have tested other movement such as turning to the left and right, but, back and forth movement keeps the robot from swerving from its trajectory. It is also easily applicable to other hardware such as manipulators. Back and forth movement is thus appropriate for the obstacle-removal task in efficiency of movement and range of application.

## 4. Experiments

We conducted experiments to verify the effectiveness of our motion-based approach in an obstacle-removal task, comparing the motion-based approach to two other nonverbal approaches.

### 4.1. Environment and Robot

**Figure 4** shows the flat experimental environment ($400 \times 300$ mm) surrounded by a wall and containing two obstacles. It simulated an ordinary human work space such as a desktop. Obstacles corresponded to penholders, remote controllers, etc., and are easily moved by participants. We used a small mobile robot, Khepera II (**Fig. 5**), which has eight infrared proximity and ambient light sensors with up to a 100 mm range, a Motorola 68331 (25 MHz) processor, 512K bytes of RAM, 512K bytes of flash ROM, and two DC brushed servomotors with incremental encoders. Its C program runs on RAM.

### 4.2. Robot Expression

Participants observed the robot as it swept the floor in the experimental environment. The robot used ambigu-

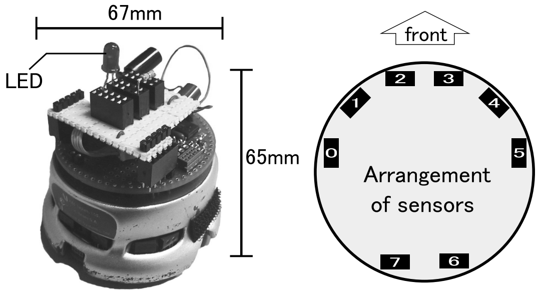


**Fig. 5.** Khepera II.

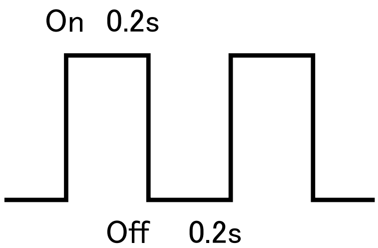


**Fig. 6.** Pattern of behavior.

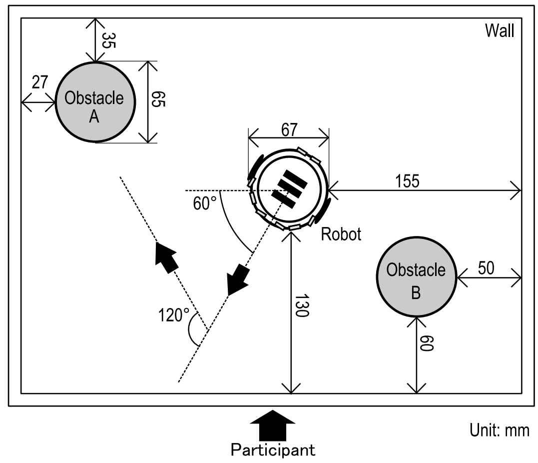


**Fig. 7.** Detailed experimental setup.

ous nonverbal expressions enabling participants to interpret them based on the situation. We designed three types of signaling to convey the robot's mind to sweep the area under an obstacle or the wish for wanting help to remove the obstacle. It expressed itself using one of the three following types of signaling:

- **LED:** The robot's red LED (6 mm in diameter) blinks based on ISO 4982:1981 (automobile flasher pattern). The robot turns the light on and off based on the signal pattern in **Fig. 6**, repeating the pattern twice every 0.4 seconds.
- **Buzzer:** The robot beeps using a buzzer that made a sound with 3 kHz and 6 kHz peaks. The sound pattern was based on JIS:S0013 (auditory signals of consumer products intended for attracting immediate attention). As with the LED, the robot beeps at "on" and ceases at "off" (**Fig. 6**).
- **Back and forth movement:** The robot moves back and forward, 10 mm back and 10 mm forth based on "on" and "off" (**Fig. 6**).

The LED, buzzer, and movement used the same "on" and "off" intervals. The robot stopped sweeping and performed each when it met an obstacle or wall, then turned left or right and moved ahead. If the robot senses an obstacle on its right (left), it makes a 120-degree turn to the left (right), repeating these actions during experiments. Note that the robot did not actually sweep up dust.

### 4.3. Methods

Participants were instructed that the robot represented a sweeping robot, even though it actually did not sweep. They were to imagine that the robot was cleaning the floor. They could move or touch anything in the environment, and were told to help the robot if it needed it.

A participant conducted three trials and saw the robot move back and forth, blink its lights, or sound its buzzer. The order of expression was random. A trial finished after the robot's third encounter with obstacles, or when the participant removed an obstacle. No information about the robot's movement, blinking, or sounding.

**Figure 7** details experimental settings that include the robot's initial locations and those of objects. At the start of each experiment, the robot moved ahead, stopped in front of a wall, expressed itself, then turned right toward obstacle A. **Fig. 8** shows the experiment. A participant sat on the chair and helped the robot on the desk.

Participants numbered 17 – 11 men and 6 women aged 21-44 including 10 university students and 7 employees. We confirmed that they had no experience in interacting with robots for the home.

### 4.4. Evaluation

We used the criterion that fewer expressions were better because this would help participants understand easily what was on the robot's mind. The robot expressed itself whenever it encountered a wall or obstacle. We counted the number of participants who moved the object just after the robot's first encounter with the object. We considered using other measurement such as the period from the beginning of the experiment to when the participant moved an obstacle, but, this was difficult because the time at which the robot reached the first obstacle differed somewhat for each trial. Slippage of the robot's wheels changed its trajectory.

### 4.5. Results

**Table 1** shows participants and behavior in experiments. Terms in bold marked by an asterisk are trial in which a participant removed an obstacle. Eight of 17

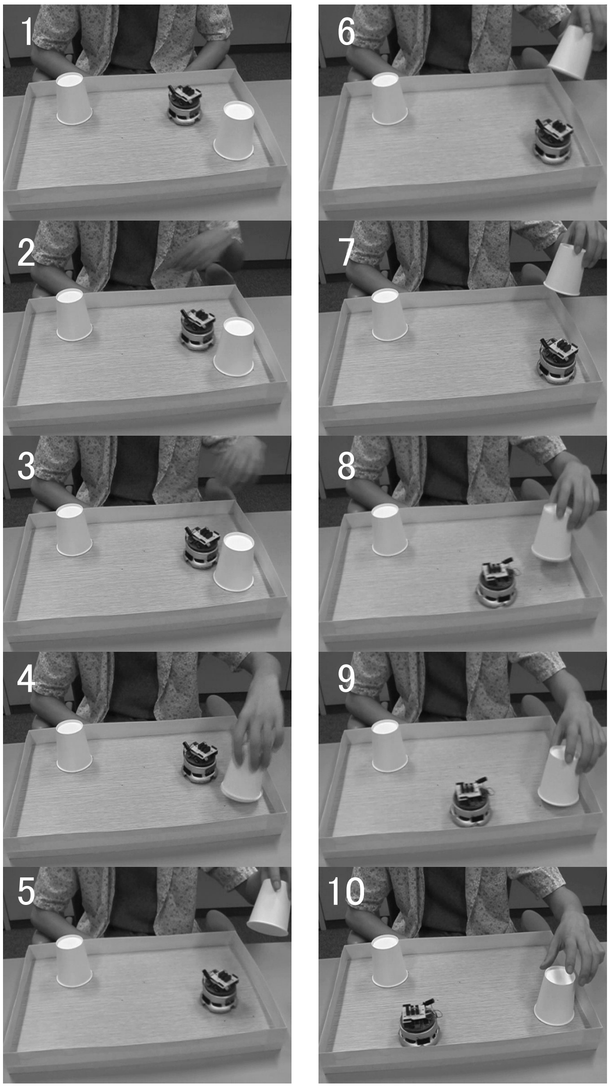


**Fig. 8.** MO experiment.

(47%) did not move any obstacle under any three experimental condition. **Table 2** shows ratios of participants moving the obstacle under each condition. Ratios increased with the number of trial. This appeared more clearly under the MO condition.

**Figure 9** shows ratios of participants who moved the obstacle immediately after the robot's first encounter with it. More participants responded to MO than to either the buzzer or light. We statistically analyzed the differences in ratios among the three methods. The result of the statistical test (Cochran's Q test) showed significant differences among methods ($Q = 7.0$, $df = 2.0$, $p < .05$). We conducted a multiple comparison test, Holm's test, and obtained 10% level differences between MO–LED ($Q = 5.0$, $df = 1.0$, $p = 0.0253$ ,$\alpha' = 0.0345$ [1]) and MO–buzzer ($Q = 4.0$, $df = 1.0$, $p = 0.0455$, $\alpha' = 0.0513$), indicating that MO is as effective or more effective than the other two methods.

1. $\alpha'$ is the modified significant level by Holm's test.

**Table 1.** Participant behavior.

| ID | Age | Gender | Trial 1 | Trial 2 | Trial 3 |
|---|---|---|---|---|---|
| 1 | 25 | M | **LED*** | **Buzzer*** | **MO*** |
| 2 | 30 | M | Buzzer | MO | LED |
| 3 | 24 | M | MO | LED | Buzzer |
| 4 | 25 | M | **LED*** | **MO*** | **Buzzer*** |
| 5 | 23 | M | **Buzzer*** | LED | **MO*** |
| 6 | 43 | F | MO | LED | Buzzer |
| 7 | 27 | M | LED | Buzzer | **MO*** |
| 8 | 29 | F | LED | **MO*** | **Buzzer*** |
| 9 | 44 | F | Buzzer | **MO*** | **LED*** |
| 10 | 26 | F | Buzzer | LED | **MO*** |
| 11 | 29 | F | MO | Buzzer | LED |
| 12 | 27 | M | LED | Buzzer | **MO*** |
| 13 | 36 | M | MO | LED | Buzzer |
| 14 | 27 | M | Buzzer | LED | MO |
| 15 | 26 | M | **Buzzer*** | **MO*** | **LED*** |
| 16 | 26 | M | MO | Buzzer | LED |
| 17 | 21 | F | LED | Buzzer | MO |

**Table 2.** Expressions and trials.

| | Trial 1 | Trial 2 | Trial 3 |
|---|---|---|---|
| LED | 33% (2/6) | 0% (0/6) | 40% (2/5) |
| Buzzer | 33% (2/6) | 17% (1/6) | 40% (2/5) |
| MO | 0% (0/5) | 80% (4/5) | 71% (5/7) |

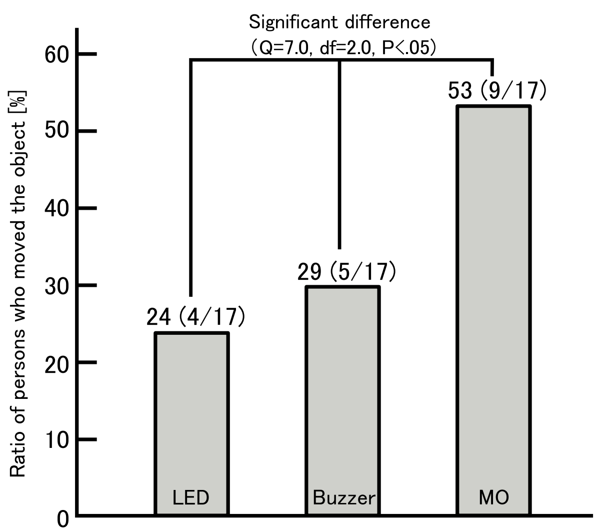


**Fig. 9.** Ratios of participants who moved the object.

In the questionnaire on experiments (**Table 3**), most participants said they noticed the robot's action. **Table 4** shows results of the questionnaire. We asked participants why they moved the object. The purpose of our design policy corresponds to question (1). More people responded positively to question (1) for the cases of the buzzer and MO. MO achieved our objective because it caused the most participants to move the object.

**Table 3.** Number of participants who noticed the robot's expression.

| | LED | Buzzer | MO |
|---|---|---|---|
| I noticed. | 15 | 17 | 16 |
| I don't remember. | 2 | 0 | 1 |

**Table 4.** Results of the questionnaire.

| | | LED | Buzzer | MO |
|---|---|---|---|---|
| 1. | I felt that the robot wanted me to move it. | 1 | 3 | 4 |
| 2. | I moved it depending on the situation. | 2 | 3 | 3 |
| 3. | I don't know why I moved it. | 1 | 1 | 1 |
| 4. | I felt some urgency. | 0 | 2 | 1 |
| 5. | Other reason. | 0 | 0 | 1 |
| | Total | 4 | 9 | 10 |

## 5. Discussion

We discuss the effectiveness and application of MO based on experimental results in the sections that follow.

### 5.1. MO Effectiveness

We avoided using loud sounds or strong lights because they are not appropriate for a home-use robot. We confirmed that participants correctly noticed the robot's expression. Results of the questionnaire (**Table 3**) showed that the expressions we designed were appropriate for experiments.

MO is not always effective in every situations because **Table 2** suggests the existence of a combination effect. Although participants experienced MO in previous experiments, only 40% of them moved the obstacle under the LED–Trial3 and Buzzer–Trial3 conditions. Under the MO–Trial1 condition, no participants moved the obstacle. Further study of the combination effect is thus important.

We used specific lighting and sound patterns for expressing the robot's mind, but, the effects of other patterns are not known. A more frequent, complex sound pattern, for example, may help users to understand the robot's mind more easily. The expressive patterns we used were a few of many. A more organized investigation on light and sound is thus needed to determine more effective patterns. Our results show that conventional methods are not sufficient and that MO shows promise.

Questionnaire results (**Table 4**) show that many participants felt that the robot "wanted" them to move the obstacle or moved it depending on the situation. The "wanted" response reflects anthropomorphization of the robot. The "depending on the situation" response may indicate that they identified with the robot's problem. As Reeves et al. [21] and Takeuchi et al. [8] have noted participants exhibiting interpersonal action with the robot would not report the appropriate reason, so questionnaire results are not conclusive. MO may, however, encourage users to anthropomorphize robots.

**Table 4** compares MO and the buzzer, which received different numbers of responses. Although fewer participants moved the obstacle after the buzzer than after MO, the buzzer had more responses in the questionnaire. The buzzer might offer highly ambiguous information in experiments. The relationship between the degrees of ambiguity and expression is an important issue in designing robot behavior.

### 5.2. MO Applications

Results for MO were more promising results than for other nonverbal methods, but are these results generalizable? Results directly support the generality of obstacle-removal tasks. We consider that an obstacle-removal task is a common subtask in human-robot cooperation. For other tasks without obstacle-removal, we may need to design another type of MO-based informative movement. The applicable scope for MO is thus an issue for future study.

Morris's study of human behavior [15] suggests the applicability of MO. Morris states that human beings sometimes move preliminarily before taking action, and these preliminary movements indicate what they will do. A person gripping the arms of a chair during a conversation may be trying to end the conversation but does not wish to be rude in doing so. Such behavior is called an "*intention movement*" and two movements with their own rhythm, such as left-and-right rhythmic movements on a pivot chair, are called "*alternating intention movement*." Human beings easily grasp each other's intent in daily life. We can consider the back and forth movement to be a form of alternating intention movement meaning that the robot wants to move forward but cannot do so. Participants in our experiments may have interpreted the robot's mind by implicitly considering its movements as alternating intention movement. Although the LED and buzzer rhythmically expressed itself, they may have been less effective than MO. Participants may not have considered them as intention movement because they were not preliminary movement – sounding and blinking were not related to previous movement, moving forward.

If alternating intention movement works well in enabling a robot to inform a user about its mind, the robot will be able to express itself with other simple rhythmic movements, e.g., the simple left and right movements to encourage the user to help it when it loses the way. Rhythmic movement is hardware-independent and easily implemented. We believe that alternating intention movement is an important element in MO applications, and we plan to study this and evaluate its effectiveness. A general implementation for expressing robot's mind can be established through such investigations. The combination of nonverbal and verbal information is important for robot expression, and we plan to study ways to combine different expression to speed up interaction between users and robots.

## 6. Conclusions

We have proposed a motion-based approach for nonverbally informing a user of a robot's state of mind. Possible nonverbal approaches include movement, sound, and lights. The design we proposed, called motion overlap, enabled a robot to express human-like behavior in communicating with users. We devised a general obstacle-removal task based on motion overlap for cooperation between a user and a robot, having the robot move back and forth to show the user that it wants an obstacle to be removed. We conducted experiments to verify the effectiveness of motion overlap in the obstacle-removal task, comparing motion overlap to sound and lights. Experimental results showed that motion overlap encouraged most users to help the robot.

The motion-based approach will effectively convey robot's mind in obstacle-removal tasks and contribute to design of robots for the home. The applicable scope for motion overlap, ways to combine different expression to speed up interaction between users and robots, and investigation into effects of alternating intention movement are issues for future study.

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