Human-Robot Interaction Design for Low Cognitive Load in Cooperative Work

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Abstract

This paper describes effective interaction design for a cooperative task in which a mobile robot sweeps over a table and a human can help it by picking up an obstacle. For efficient cooperation, we introduce behaviors of a robot to sweep a region under an obstacle when a human picks up it vertically, and design the robot based on interaction embedded in a human's operations to achieve a task. This interaction enables a human to easily cooperate with a robot without additional and explicit commands. We made experiments to evaluate the interaction embedded in a task by comparing with other explicit interaction, and the experimental results show our cooperative sweeping is more efficient than autonomous one and our interaction embedded in a task needs less cognitive load than other explicit interaction such as voice or leading the robot by hand.

1 Introduction

Home robots such sweeping robots, carrying robots begin to spread among people through progression of robot technology [1]. Most of the home robots are designed to autonomously achieve every life task such as seeping rooms, carrying baggage and so on. However, it is not practical that such an autonomous robot completely achieves its task by itself. For instance, a home robot "Roomba" can sweep a room autonomously and it is very useful to sweep a simply structured room without obstacles like a chair or a trash can. However, a human actually needs to help the robot by removing obstacles, since it cannot remove such obstacles during sweeping. Thus designing a robot to cooperate effectively and efficiently with a human is important.

Various researches have been studied in a field human-robot interaction [2] [3] [4] [5] [6] . Most of the researches have tried to develop a robot that communicates explicitly with a human by gesture [7] [8] [9], speech [10] and other ways [11][12] . Explicit interaction has been applied to communication between a human and a robot, it is however inappropriate for human-robot cooperative work in terms of user's cognitive load because it forces a user to become familiar with explicit communication protocol.

Meanwhile, implicit interaction has been utilized for human-robot cooperative work. These are studies for carrying a long object [13] [14] , handling an object [15] , outdoor cooperative tasks [16]. Unfortunately these studies lack generality as a framework for human-robot cooperation. First, their implicit interaction is restricted in force and physical connection between a human and a robot. Second, their cooperation has low applicability because it limited between actions. Cooperation between tasks including actions has high applicability.

There are no study providing generality and utility for human-robot cooperation. We therefore propose an interaction design of IET (Interaction Embedded in at Task) and apply it to human-robot cooperative sweeping over a table. This IET leads low cognitive load of human because it does not need to understand human-robot communication protocol, and it needs no additional actions for a human task. IET thus has both generality and utility.

After the introduction, in Section 2, we define IET by embedding implicit commands in a human's operations to achieve his/her task. In Section 3, we apply IET to design a cooperative sweeping robot and its interaction with a human. A developing of a behavior-based robot is described in Section 4. Section 5 describes experiments to investigate efficiency of cooperative sweeping and compare IET with other explicit interaction such as voice or hand manipulation in terms of human's cognitive load. The experimental results are indicated in Section 6. Finally, Section 7 concludes this paper.

2 Interaction Embedded in a Task

The interaction embedded in a task is "the minimum additional interaction (including robot commands) in terms of time and space cost to typical human's actions for a task." We call this interaction as IET, and it has advantages described as follow:

- No additional cognitive load in execution:
  Since IET has minimum additional interaction to typical human's actions to achieve a task, a human does not need additional cognitive load by explicit communication with a robot and smoothly does cooperation with a robot by executing only typical actions.
- No understanding a way to communication:
  Since explicit communication is not necessary in IET, a human does not need to understand communication protocol like gesture commands, special speech commands. IET thus releases a human from learning protocol and training to communicate with a robot.

3 Interaction Design on Cooperative Sweeping

We deal with a human-robot cooperative sweeping between a human and a small mobile robot as a cooperative work. A goal of the cooperative task is to sweep out a desk including the region of under an object, human's task is to move the object, and robot's task is to sweep out a desk. The hardware resource of a robot is equal to that of a consumer sweeping robot. Since a robot cannot move an object by itself, cooperative task of cleaning is achieved when a human and a robot work out their task cooperatively.

In this section we first describe an experimental environment and a specification of small robot. And then we consider an effective cooperation which shortens the time of whole environment sweeping on human-robot cooperative sweeping. The effective cooperative work is achieved through IET.

3.1 Environment and robot

Fig.1 shows an experimental environment where a human and a robot work cooperatively. This environment simulates a place where a human uses routinely such as a desktop. A desk where a robot sweeps out has flat surface and a wall which encloses the region for keeping a robot not to fall.

We use a small mobile robot KheperaII. The robot has eight infrared proximity and ambient light sensors with up to 100mm range, a processor Motorola 68331 (25MHz), 512 Kbytes RAM, 512 Kbytes Flash ROM, and two DC brushed servo motors with incremental encoders. The program written by C-language runs on the RAM. An extra infrared sensor which measures the distance in vertical direction is added on its general I/O turret.

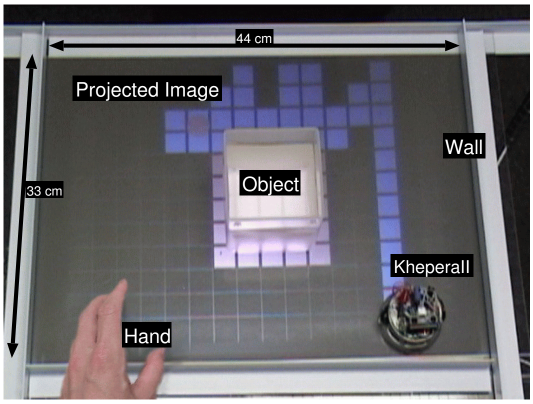

Figure 1: Experimental environment

3.2 Cooperative sweeping by IET

Fig.2 shows cooperative sweeping through IET by a human and a robot. We consider this cooperative work shortens the time of whole environment sweeping, and leads low cognitive load. The procedure is described as follow:

(1) A human picks up an object when a robot approaches an object. Then a robot comes into the region under the object picked up.

(2) While a robot is in under an object, it keeps turning at the object's edge.

(3) A robot goes out of the region when a human approaches an object to it.

The human's action has no changes in the trajectory from the typical one, and it has little additional time to keep picking up. A human does not need to move an object to another place. Since the minimum change of the action trajectory and the minimum cost of time, this interaction forms IET. When no commands are embedded in human's task, a human has to achieve two tasks at least. He/she needs to control a robot explicitly to work well and to replace an object as his/her assigned task. On the other, IET can reduce his/her loads without sending explicit commands.

4 Behavior Design of Mobile Robot

Our robot performs obstacle avoidance, going forward (when no obstacles are on its front) and turning for random direction. We use sweeping with selecting directions at random because it has lower cost than a

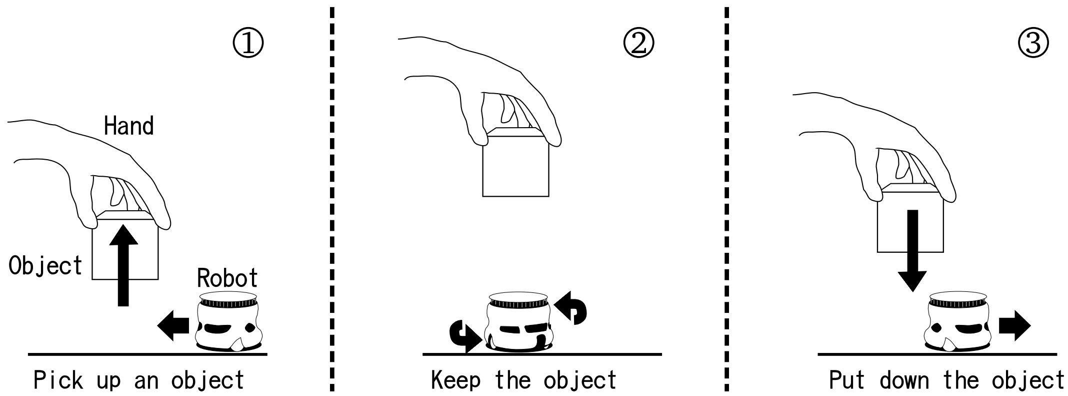

Figure 2: Cooperative sweeping by IET

calculated sweeping using a map. Many methods for region covering have been developed[17], and most of them need precise position of a robot. However, our robot can not use reliable methods like dead reckoning. We hence consider that the random sweeping is adequate to our study because the most of consumer sweeping robots adopt this kind of method.

A robot is implemented by behavior-based approach, and we adopt subsumption architecture[18] to manage following behaviors.

- Obstacle avoidance.
- Autonomous sweeping while no object is sensed.
- Interactive sweeping while an object is above a robot.

Fig.3 shows the robot's behaviors into the three layers in subsumption architecture. Each layer asynchronously checks the applicability of behaviors and executes applicable ones. Higher layers suppress lower layer's behaviors, and lower layers have more reactive behaviors. The behaviors of each layer consist of multiple actions. When the system obtains multiple outputs, it generally selects the highest layer's action. Each layer has output frequency of action to control the robot smoothly. We set the frequency as obstacle avoidance: an action by 5msec, sweeping: 10msec, interaction: 5msec, obstacle avoidance and interaction occur most frequently.

5 Experiments

We conduct two experiments. In a first experiment, we confirm whether a robot improves cleaning time by using a behavior of a cooperative sweeping through IET. In a second experiment, we examine human cognitive load when a human interacts with a robot through IET in a cooperative work of cleaning on a desk. Both experiments are performed on our experimental system described in the next subsection.

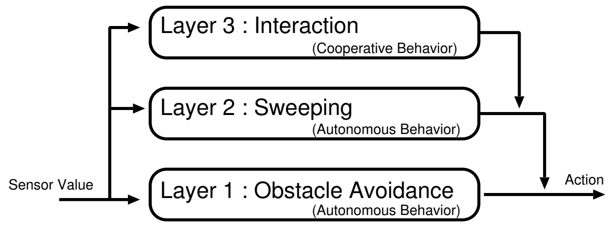

Figure 3: Subsumption architecture

5.1 Experimental system

Fig.4 shows the experimental system which can indicate a robot's trajectory. This system consists of a sweeping area and a projection system. In experiments, a human interacts with a robot on the sweeping area in Fig.1 indicating a swept location by the projection system including a personal computer, a projector, and a USB camera.

The projection system detects a robot's location using a picture of two beams of infrared LEDs equipping on the robot. The robot's location is calculated by image processing in the picture from the camera, and then an image indicating the trajectory is created with the location. This image is ultimately projected on the sweeping area.

The projected image also includes small square cells. A cell is lit when a robot enters the cell in real time. These small cells therefore express the trajectory of a robot. The sweeping area having a width of 44 cm and a height of 33 cm is divided into 16 $\times$ 12 cells. Cells of 3 $\times$ 3 approximately correspond to the

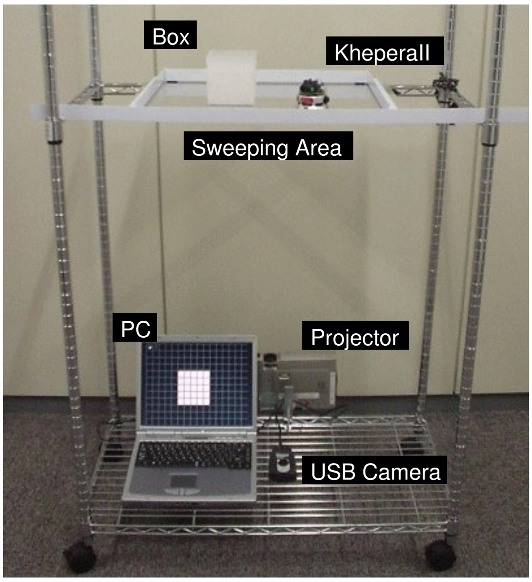

Figure 4: Experimental system

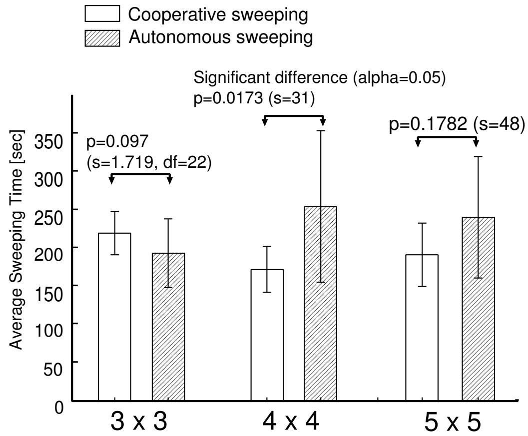

Figure 5: Result of average time in each size of boxes

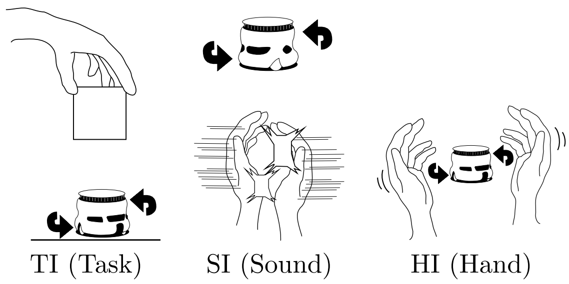

Figure 6: Three types of interactions

area of a robot.

5.2 Ex.1: Sweeping efficiency

The purpose of Ex.1 is to confirm that the time of cooperative sweeping is shorter than that of autonomous sweeping. We measure the time until the robot covers the 98% of all cells in three cell sizes of boxes : 3×3, 4×4, 5×5. A sweeping time is measured 3 times in each size of boxes. The initial location of a robot and a box are determined at random in each measuring. Larger sizes of boxes (such as 6×6) are not employed, because these conditions make a free space too small and narrow for a mobile robot to fully sweep there.

In cooperative sweeping, a subject continues to pick up an object until all the cells of under the object are swept, and he puts down it. After that he performs no actions. In autonomous sweeping, on the other hand, a subject relocates the box to the place decided beforehand when the experiment begins. He puts down the box to the initial location when those cells are swept, after that he performs no actions.

5.3 Result of Ex.1

Fig.5 shows average times of sweeping in each size of boxes, error bars indicating their standard deviation, and differences of each size of boxes between cooperative sweeping and autonomous one. This experiment was performed by a subject of a late 20s man. Each pare of average times are tested by t-test or Wilcoxon's rank sum test. As a result, the 4×4 box has a significant difference of sweeping time ($p = 0.0173, \alpha = 0.05, statistic = 31$).

5.4 Ex.2: Human cognitive load

We measure the cognitive load of a human interacting with a robot through IET, and compare the load to that of explicit interaction. These loads are investigated by using robots interacting with a human through three types of interaction. These interactions are shown in Fig.6, and the detail is described as follow:

TI : A robot performs sweeping through IET.

SI : A robot sweeps with receiving a sound command by hand clapping.

HI : A robot sweeps with receiving a command by hand as blocking the robot's line.

Each robot performs cooperative sweeping in different interactions. The last two robots receive each explicit command which a human sends besides his/her task of raising a box. We choose these two methods for sending command because they need no extra special devices such as a remote controller, and a human can create a command by only his/her body.

The experimental system is the same as Ex.1, and the 4×4 box is selected because it has a significant difference in the result of Ex.1. One of the experiments runs until the all of 16 cells are swept. In the TI, subjects pick up an object until all the cells of under the box are swept. In the SI and HI, first, they relocate a box to a corner of the sweeping area, and then send a command for a robot to be turn by making sounds or approaching their hand to it.

We use a dual task method to measure human cognitive load. Subjects have to do mental arithmetic as a second task while controlling the robot as a main task[19][20]. They count backwards by three from a randomly selected three-digit number vocally. We obtain the average number of correct answers per second, and evaluate the human's cognitive load for controlling each robot. Subjects are required to calculate as quickly as possible, and to prioritize the controlling a robot over the counting. They practice controlling robots and the counting well before experiments begin. The order of TI, SI and HI for each subject is determined at random, and these experiments are recorded three times respectively for a subject. Subjects are also measured counting ability without operations of a robot before a measuring of TI, SI, or HI respectively. The counting ability is the number of correct answers of the counting for 30 seconds.

5.5 Result of Ex.2

Fig.7 shows scores for 12 subjects. They are 8 men and 4 women between the age of 22 to 32. In the figure, each subject has three scores: TI, SI, and HI. A score is the average of normalized number of correct counting answers per second for a subject. The normalization is to divide the correct answers per second by correct answers per second without operations of a robot. Therefore, 1.0 means counting ability of each subject without operations of a robot. The figure also includes averages of TI , SI, and HI. TI has the highest average. Fig.8 shows averaged scores, standard deviations and differences tested by Dunnett's test. The difference between TI and HI has a significant difference ($p << 0.01, \alpha = 0.01, t = 3.938$). The difference between TI and SI also has a significant difference ($p = 0.033, \alpha = 0.05, t = 2.414$).

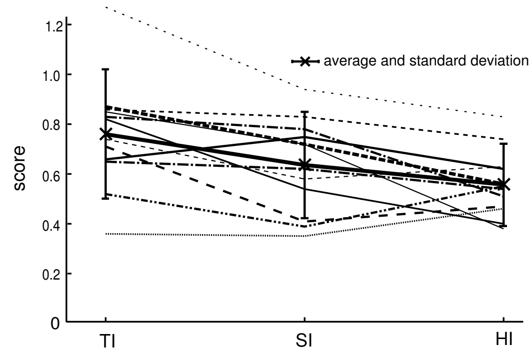

Figure 7: Result of score in each subject

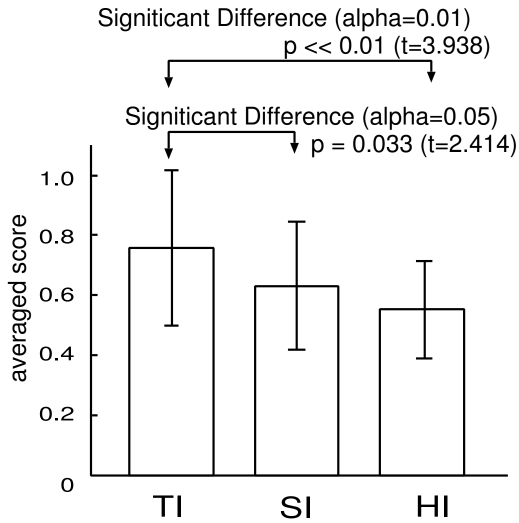

Figure 8: Result of scores and differences

6 Discussion

The result of Ex.1 shows that the cooperative sweeping made the whole area sweeping efficient, and it depends on proportion of the size of box and the size of the whole sweeping area. This effect however is available only for the random sweeping strategy, and can be applicable not only in the case of using the IET, but in the case of using the explicit commanding interactions. We conform that such cooperation shorten the sweeping time significantly and how to design an interaction for drawing human's operations toward cooperative sweeping. Our IET plays an important role on this issue.

The result of Ex.2 shows that the IET minimizes human cognitive load in comparison with other explicit commanding interactions. An additional task of sending command has high cognitive load in explicit interaction and we consider that physical loads affect the counting task as well. On the other hand, IET has low cognitive load because of minimizing cost of sending a command and also shortening the trajectory of moving a box. Therefore, IET plays the significant role in human-robot cooperative work.

7 Conclusion

We design an interaction for reducing human cognitive load, which is an IET (Interaction Embedded in a Task) for human-robot cooperative work, and the interaction includes an embedded command within a human's action for achieving his/her task. This interaction enables a human to easily cooperate with a mobile robot without additional and explicit commands. A real small robot's behaviors are implemented to sweep cooperatively with a human through IET. We conduct two experiments. In a first experiment, we confirm whether a robot improves cleaning time by using a behavior of a cooperative sweeping through IET. In a second experiment, we examine human cognitive load when a human interacts with a robot through IET in a cooperative work of cleaning on a desk. The first experimental result showed that the cooperative sweeping made the whole area sweeping efficient, and the second experimental result showed that IET minimized human cognitive load in comparison with other explicit commanding interactions. These results show that a robot with poor hardware resource can work cooperatively with a human, and IET reduce human cognitive load in a human-robot cooperative work.

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