Aiming at realization of direct and intuitive communication between human and robot, we propose an interface system for an autonomous mobile robot that can take physical communication with its user via haptic, or hand-to-hand force interaction. The hand-shaped device equipped on the robot has 1 DOF at the finger part and is capable of grasping a human hand when actuated. A micro-switch on the bottom side of the hand is used to sense grasping of human. Intentional force information is acquired by strain gages on the flexible rubber-made arm that physically supports the hand. The robot’s motion is determined by the force input and/or the environmental condition. The robot recognizes obstacles by using bumper sensors and ultrasonic sensors around the body. When it touches an obstacle, the robot changes the route regardless of the user’s intentional force and thus informs the user of such situation of obstacle avoidance. In this research, we design simple algorithms for both human-following and human-leading motions, and devise experiments with human users. Qualitative and quantitative evaluations of the experimental results are also presented.

Key Words: human-machine interface, human-cooperative robot, haptic interface, “Kansei”, force interaction

1 Introduction

1.1 Background

Arguably the most popular media tool of information and communication in the past few decades has been television. In recent years, computer has emerged as the more interactive multi-media tool and is growing in number extremely. Including these two above, most of the multimedia devices practiced in human communication today are realized in forms of either sound or images. In approach to more informative multi-modal communication, utilization of force information seems to be effective. Many researchers have proposed application of haptic or hand-to-hand force interaction to their newly designed media devices. In our laboratory, some reports have been made to realize haptic interaction between human users in distance. The handshake telephone system utilizes grasping force information [1] and the haptic and tactile telecommunication system both force and tactile information [2], in order to examine capability of haptics as another medium for digital human communication.
But when thinking about applying force information to multi-media communication, such media devices must have physical structure that can be actuated. Unlike other perception, force sensing and exerting processes require respective physical action. It is expectable that active apparatus like robots becomes new media of human communication in the close future. In fact, the recent development of robot interface development has been clearly shifted to multi-modal utility. As robot interfaces become multi-modal, there seems to be various possibilities in application of robotic systems as new type of active multi-media terminal.

1.2 Human-Cooperative Robots

By the way, prevailing trends of robot researches today includes application of human-friendly robots to daily operations in human environment. Robots are now required to hold more and more works in human environment such as in fields of nursing, aiding, entertainment, etc, and the stance of robots is shifting from “in place of human” to “with human”. But since it seems to require more time until appearance of self-controlled autonomous mobile robots that work without any support from others, considerable attention of researchers have been drawn to development of human-cooperative robots. These robots operate as acquiring support from human and thus believed to be more practical than self-controlled robots.

There are several papers on human-robot cooperation efficiently achieved by applying force information to the robotic systems. [3-6,10]. Kosuge has recently developed an armed robot that can carry object in cooperation with a human, and multiple mobile robots that carry a large or heavy object in distribution [3]. Method of compliant motion control based on the Virtual Internal Model is also reported [4]. Cooperative carrying task by a human and a manipulator robot with Variable Impedance Control [5] and human-following experiment with biped humanoid robot are achieved as well [6]. All of the above utilize force information in achieving cooperative tasks or communication, but most of them hardly have essential design to be human interface. Efficient interface system for human-robot cooperation must afford, or appeal to “Kansei” of, human users to interact with the robot. “Kansei” is a human ability of making perception in non-logical way [7]. In addition, the study of interface system utilizing force [8] suggests that handling, safety and impression are also important factors.

Cooperation between human and robots may require massive transactions of information. Robots must be able to profoundly interact with human users because human characteristics are unknown and operational environment is dynamically changing [9,10]. Multi-modal interface systems can be very helpful for such human-robot communication. While perceptual, auditory, and linguistic communication systems are often too immense to be implemented on autonomous
mobile robots and existing interfaces such as keyboards, touch panels, and remote controllers lacks intuitiveness, force interaction system can provide direct and intuitive physical interaction with considerably simple application.

1.3 Haptic Interaction and Application to Robot Interface

One of the most intuitive communication methods between humans is haptic interaction. Hand-to-hand force interaction provides us transactions of direct physical force information as well as a favorable mental effect of togetherness, amiability, and security. It seems efficient to utilize haptic interaction in an interface system of human-cooperative robot.

Thus we propose the hand-shaped force interface for the autonomous mobile robot that can take haptic interaction with the human. In achieving human-robot cooperation, we suppose the robot can communicate with its user only through haptic force interaction by using the hand-shaped force interface.

The hand-shaped device is actuated at the finger part with 1 DOF to achieve gentle grasp. The force information is acquired by the strain gages that are attached on the flexible rubber-made arm physically supporting the hand. The robot's motion is determined by the force input and/or the environmental condition. Fundamental obstacle recognition is achieved by using bumper sensors and ultrasonic sensors around the body. The robot informs the user of obstacles he/she is not aware of by changing the route regardless of the intentional force direction. We design Simple algorithms for both human-following and human-leading tasks. We devise experiments with human users for each task. Qualitative and quantitative evaluations are presented to examine the system’s efficiency. We also mention about possible future application of the system as multi-media interface.

2 System

This section explains the structure and function of the interface system in application to the human-cooperative mobile robot. First, we introduce the base mobile robot. Then, we view the whole system and function of the proposed force interface.

2.1 Robot Body

The robot we use in this research is two-wheeled mobile robot that can move forward/backward and rotate clockwise/counter-clockwise (Figure1). Obstacle sensors equipped on the robot body are bumper sensors and ultrasonic sensors. The bumper sensors are equipped in front and on the tail of the base body and can sense obstacle contact in six different directions (Figure2). The ultrasonic sensors are mounted to detect obstacles in distance in the robot’s forward direction.
2.2 **Interface Structure**

Appearance of the whole robot is shown in Figure 3. The haptic, or force, interface system is composed of the hand-shaped device supported by the flexible arm. The hand part is made of a plastic skeleton covered with a rubber glove, and is capable of gentle grasp with 1 DOF at the fingers. When the hand part is grasped, it is actuated to grasp back the human hand. The arm part is made of two rubber sticks, one vertically fixed on the top of the robot body and the other horizontally on top of the vertical one.
2.3 The Arm Part and Force Sensing

The rubber-made arm part that is physically supporting the hand part can easily be bent when an intentional force is exerted to the hand. Flexibility of the arm thus provides a structural compliance to the system, meaning the human user can handle the interface almost freely regardless of robot’s motion and orientation. We adopt the Four Active Gage Method for measuring the intentional force exerted to the hand part. Each set of the two strain gage bridges (one on the vertical part of the arm and the other on the horizontal part) outputs an independent force/torque information corresponding to the bend in a particular direction, that is, either forward/backward or clockwise/counter-clockwise (Figure 4). The separation of as well as the linearity of the force sensor output has been confirmed in the experiment (Figure 5).
2.4 The Hand Part and Grasping

On the bottom side of the hand part is a micro-switch as a human grasp sensor (Figure 6). When the hand part is grasped, the micro-switch turns on, and as the robot recognize its hand being grasped, it actuate the finger part to respond with gently grasping back the human hand.

In order to realize the grasping, an electro-thermal actuator (BMF250, Toki Corporation [11]) is used. This is made of threadlike Shaped Memory Alloy (SMA). It contracts like muscles when electric current flows, and it elongates when cooled. The 1 DOF fingers are directly attached to the actuator and thus grasp action is realized (Figure 7).

![Figure 6 The micro-switch sensor on the bottom side of the Hand Part](image)

![Figure 7 The structure of SMA actuator](image)
3 Control

This section describes how to control the whole robotic system with the proposed interface.

3.1 Control Structure

The intentional force exerted to the interface system gives the set point of the robot’s mobilization control. Figure 8 shows the entire structure of the motion control system. The algorithm is described in the following section.

The control of the grasp mechanism is open-looped, and the grasping force is determined experimentally.

![Diagram of the control structure](image-url)
3.2 Algorithm

We have developed two different algorithms, one for human-following task and the other for human-leading task. With the human-following algorithm, the robot moves so as to cancel out the intentional force exerted to the hand-shaped interface (Figure 9). With the human-leading algorithm, route of the robot’s leading task is given in advance, and the robot executes the task unless an excessive counter-directional force is exerted (Figure 10). When the human follower pulls the robot’s hand toward the opposite direction of the leading motion, the robot stops executing the leading task until the intentional force ceases, meaning the follower can catch up the motion delay. In both algorithms, when the robot touches an obstacle, it executes “obstacle avoidance motion (Figure 11)” regardless of the intentional force input by the human partner. Since the robot and the partner are taking hands of each other, force information can be directly communicated, and thus the robot can provide the obstacle information to the partner. The robot and the human can avoid obstacles cooperatively even in case of the human not aware of obstacles.

![Algorithm flow chart of human-following task](image)

Figure 9 Algorithm flow chart of human-following task
Figure 10 Algorithm flow chart of human-leading task

<table>
<thead>
<tr>
<th>Direction of Force/Torque</th>
<th>Robot’s motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>front</td>
<td>move backward for about 1[sec]</td>
</tr>
<tr>
<td>left-front</td>
<td>rotate counterclockwise for 30[deg]</td>
</tr>
<tr>
<td>right-front</td>
<td>rotate clockwise for 30[deg]</td>
</tr>
<tr>
<td>tail</td>
<td>move forward for about 1[sec]</td>
</tr>
</tbody>
</table>

Figure 11 “Obstacle avoidance motion” in human-following task

4 Experiment

In order to examine the efficiency of the proposed interface, 3 different experiments are devised. First, human-following and human-leading experiments are executed, and then, efficiency of the proposed interface system is evaluated in comparison with other existing interfaces.
4.1 Human-Following Experiment

In this experiment, the human user leads the robot from the start point to the goal point in two-dimensional static environment. Motion Capture is used to acquire the trajectories of the human and the robot (Figure 12) and the fluctuation of the distance between them during the task (Figure 13). These results support the achievement of the elementary human-following task.

![Figure 12: Trajectories of the human and the robot in the Human-Following Experiment](image1)

![Figure 13: Fluctuation of distance between the human and the robot in the Human-Following Experiment](image2)
4.2 Human-Leading Experiment

In this experiment, the human volunteers are requested to follow the robot’s lead with an eye mask on. The robot is programmed to execute the human-leading task in the experimental environment as shown in Figure14. The average goal time of the human-leading tasks 10 volunteers is comparable to the goal time of the robot moving by itself without human follower (Figure15). This suggests that an effective human-leading task is achieved. Result of the questionnaire after the experiment supports our proposition as well (Figure16)

![Environmental map of the Human-Leading Experiment](Image)

**Average goal time of 10 volunteers led by the robot**

<table>
<thead>
<tr>
<th></th>
<th>29 [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal time of the robot when moving by itself without human follower</td>
<td>23 [sec]</td>
</tr>
</tbody>
</table>

**Figure15 Goal time of the tasks with and without human follower**

<table>
<thead>
<tr>
<th>Question</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) was able to feel intentional force from the leading robot</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>2) felt securely lead to the goal</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

**Figure16 Questionnaire answers of the Human-Leading Experiment**
4.3 Comparative Experiment of Interface

In order to evaluate efficiency of the interface system, a comparative experiment is also held with the help of the same 10 volunteers. Two other different types of the existing interface devices along with the hand-shaped force interface are used for comparison (Figure17). In the same experimental environment as shown in Fig.14, this time, the volunteer users are requested to lead the robot from the start to the goal. Two of the examined interface devices are a digital joystick and a remote controller. Each interface device, as well as the hand-shaped force interface, is handed to the user without any instruction. Leading tasks begin when the user confidently feels that he/she has learned enough to handle the robot with each interface. The average goal time of all users suggests that the hand-shaped force interface is useful in executing such task (Figure18). Afterwards, questionnaire on qualitative evaluation is held. In each category, users must rank the interfaces in order of quality. The scores are given in integers from 3 (best) to 1 (worst), and none of the scores must be repeated more than once. The result supports that the newly designed interface excels in all factors of human interface, especially in affordance, or “Kansei” appeal, and impression. Handling of the interface seems also as efficient as other two (Figure19).

![Figure17](image17.png)

<table>
<thead>
<tr>
<th>Type of Interface</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average goal time</td>
<td>39</td>
<td>30</td>
<td>45</td>
</tr>
</tbody>
</table>

**Figure18** Average goal time of using different interfaces in comparative experiment
5 Conclusion

In this paper, the hand-shaped force interface for human-cooperative mobile robot is proposed. By utilizing hand-to-hand force interaction, profuse communication with intentional force between a human and a robot is achieved. In the human-following task, the robot not only follows the human user to the direction in which the intentional force is exerted, but also recognizes obstacles and communicates that information to the user. In the human-leading task, the robot moves as it is pre-programmed. It stops when the human follower exerts intentional force to the opposite direction of its motion. As for evaluation of the proposed robotic system, we experimented on both tasks in real human-robot cooperation. Efficiency of the human interface system is also testified in comparison to other interfaces. The experimental results suggest that the proposed system fulfill the important requirements of human interface. The developed system can be another alternative for multi-modal robot interface.

Now, we are planning to apply a velocity/acceleration control to the robot for achieving smooth motion. We are also considering on supplementing utilization of sound information for more informative communication between a human and a robot.

Possible future application of the interface system includes realization of cooperative carrying task between a human and a robot, and integration to the two-wheeled humanoid robot, in achieving interactive performance with a human such as dance and cooperative carrying with human.
References