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Collaborative Task Execution by a Human and an Autonomous Mobile Robot in a Teleoperated System

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ABSTRACT: In this paper, we describe the human-robot collaborative task execution in a teleoperated system under the restricted condition of limited feedback information. The system realizes the remote maneuvering of an omni-directional mobile robot via the Internet using a joystick. The only feedback information to the operator consists of the images from the onboard camera of the robot. Thus, the operator has to maneuver the robot with limited information from the remote site. In such a case, the robot's autonomous functions should manage lower level controls, such as collision avoidance. We have constructed a collaborative teleoperation system of an omni-directional mobile robot equipped with several sensing systems.

INTRODUCTION

The conventional teleoperation system for controlling an autonomous robot is basically a supervisory system, in which the operator gives higher level commands to the robot, and the robot executes tasks autonomously according to the given commands. However, there are technical problems in developing such a system Asama et al. (1994), and particularly with the autonomous functions that allow a robot to complete an entire task independently. Because of these problems, ideally, the high level functions for task execution should be well shared by the operator and robot. This goal has led to the design of a "Collaborative" teleoperation system based in equal parts on the autonomous functioning of the robot and the intelligence of the human operator. This type of teleoperation system is particularly useful when feedback information from the remote site is limited.

Cooperation between humans and robots has recently been discussed from a number of viewpoints, including that of the human-machine cooperation systems (Chan and Childress, 1990; Kazerooni, 1990; Koide et al., 1993; Kosuge et al., 1993; and McKee and Schender, 1995). Suzuki et al. (1996a,1996b) proposed a system for operating multiple mobile robots by means of 3 command levels: Task Level, Action Level and Direct Control Level. The Direct Control Level, the full detail of which remain to be established, controls the robot directly through transmitted signals. At such a level, it is very difficult to give the operator all the needed information of the remote environment. Thus the intelligence of the robot becomes local intelligence of the system and assists the operator in task execution. Such an intelligence level can be realized using conventional techniques and devices.

In this paper, we propose a human-robot collaborative teleoperation system. In the second section, we describe a basic teleoperation system that targets an omni-directional mobile robot. In the

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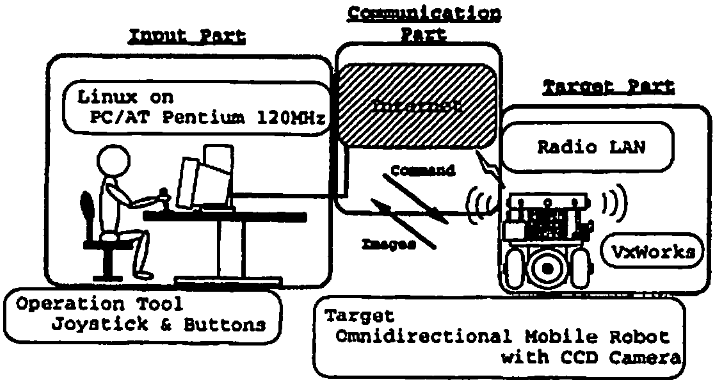


Figure 1 Robotic teleoperation system.

third section, we describe our proposed strategy for improving the conventional mobile robot teleoperation system. In the fourth section, we construct a mobile robot teleoperation system based on our strategy. In addition, we operate an omnidirectional robot through the Internet using a joystick as an input device. Finally, in this section we also confirm the validity of the proposed method in experimental trials using the real system.

TELEOPERATION SYSTEM

System Configuration

Figure 1 shows the overall configuration of the collaborative teleoperation system. This system consists of three major parts: an operation system, communication links, and a target system. A joystick is used as an input device for the operation system. The trimming direction of the joystick command to each of the different commands for the target system. Also, a wireless LAN system provides the system with TCP/IP based communication links between a PC and the target system. In this paper, the target system is an omni-directional mobile robot and its mobility is suitable for the assigned tasks. Here, we assume that the remote environment is unknown to the operator, and that the only feedback information consists of the images captured by a CCD camera mounted on the robot. Figure 2 shows the setup of the input device and the display system of our teleoperation system. The operation system employs the Linux operating system, which is a type of PC UNIX and free software. In addition, the mobile robot employs a real time operating system named VxWorks. In this system, the mobile robot becomes a physical agent on the network. In other words, the robot acts as an intelligent mobile PC system with wheels.

Omni-directional Mobile Robot

Figure 3 shows an omni-directional mobile robot with specially designed wheels. Its drive mechanism realizes omni-directional motion and a decoupled control of 3 DOF in the horizontal plane Asama et al. (1995). Figure 4 indicates the special drive mechanism which mainly consists of 4 wheels with free rollers, 3 DC-motors and differential gears. The mechanism realizes omni-directional mobility. Due to this fact, the operator can operate the robot according to the operator's judgement and recognize the robot's situation and motion. The robot carries a CCD camera with pan-tilt and zoom-in functions (Figure 5). The specifications of the camera are as follows:

- pan-motion range is from -50 [deg] to 50 [deg], but the robot can rotate 360 [deg];
- tilt-motion range is from -20 [deg] to 20 [deg];
- horizontal view field is from -20 [deg] to 20 [deg];
- vertical view field is from -15 [deg] to 15 [deg];

Images captured by the CCD camera constitute the feedback information to the operator in the proposed collaborative teleoperation system.

Also, two kinds of sensor systems, an ultrasonic range finder and infrared sensor system for acquisition of the external information, are the key devices in this collaborative teleoperation. Figure 6 shows the sensor unit mounted on the robot. The sensor system consists of 8 channels of ultrasonic range finders and infrared sensors with local communication systems known as LOCISS (Locally Communicable Infrared Sensing System) Arai et

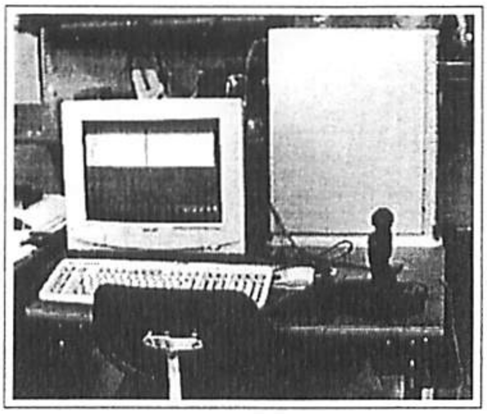


Figure 2 Input device of system.

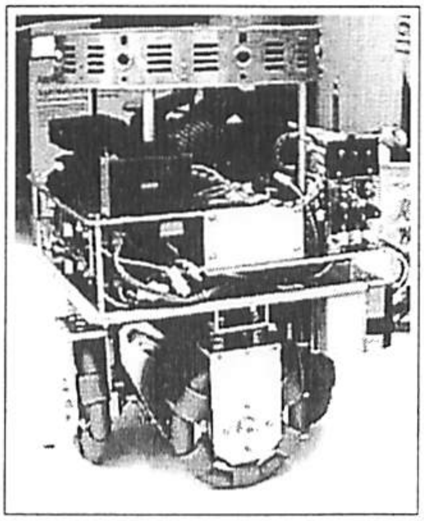


Figure 3 Omni-directional mobile robot.

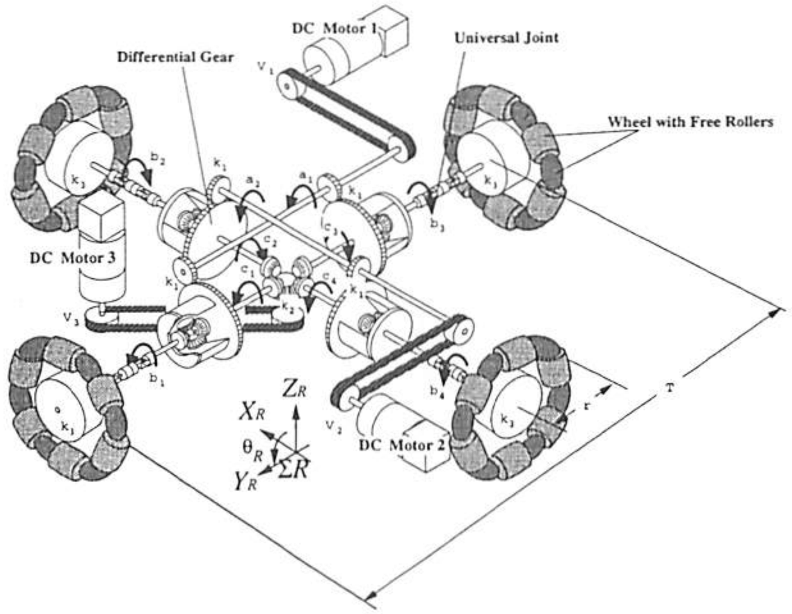


Figure 4 A special drive mechanism.

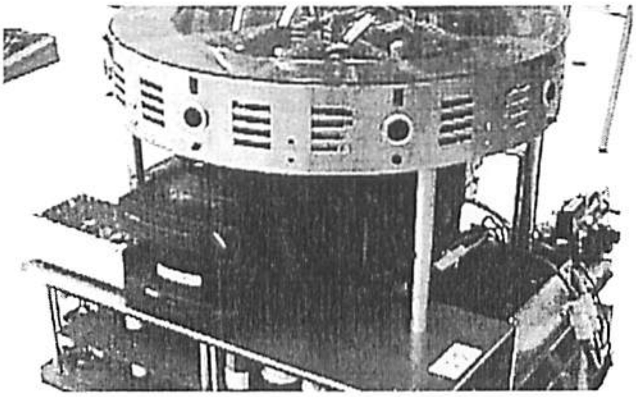


Figure 5 CCD camera on the robot.

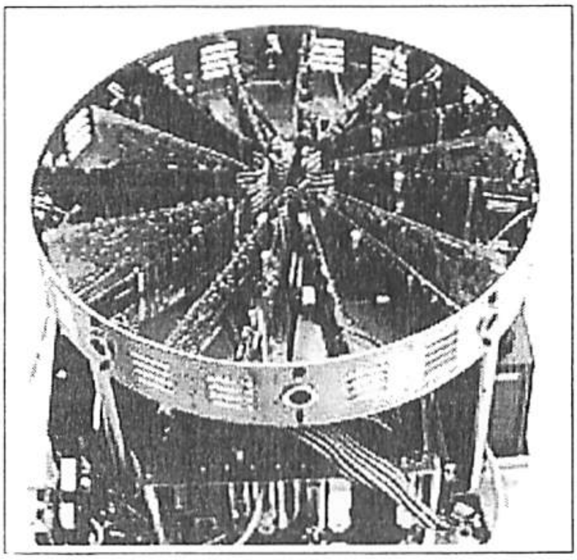


Figure 6 Overview of sensor unit.

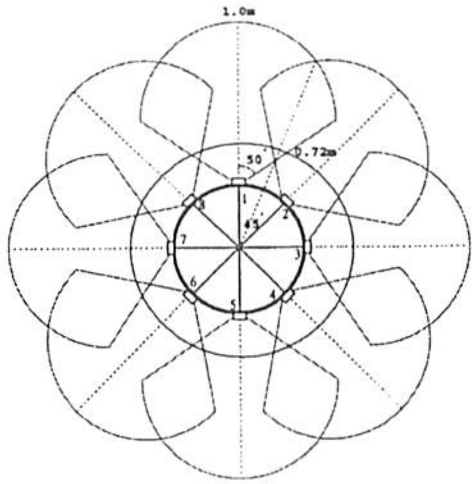


Figure 7 Measurement area of ultrasonic sensors.

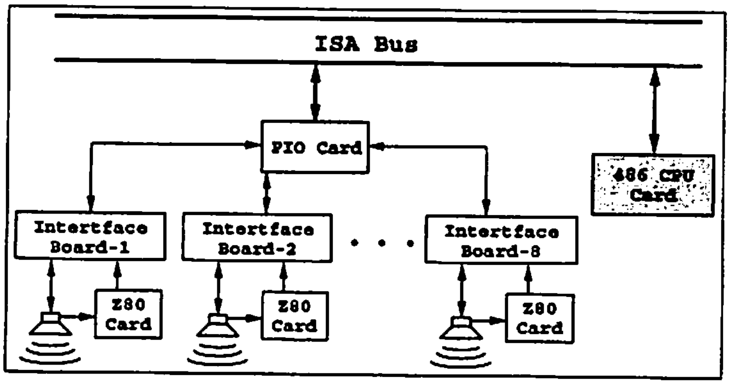


Figure 8 Connection of controllers.

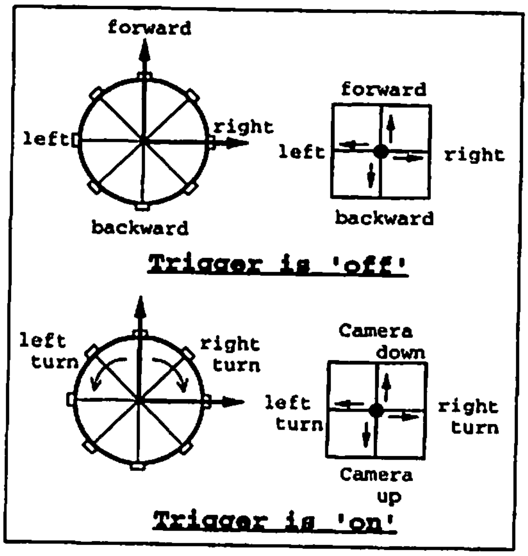


Figure 9 Motion assignment.

al. (1996). LOCISS covers the entire range around the robot. Each infrared sensor unit transmits the signal with its own ID numbers. This system realizes both obstacle detection and local communication with other robot. The ultrasonic range finder units also cover the entire range around the robot. There is no blind direction (Figure 7), and the units can measure the distance from 0.3 [m] to 1.0 [m]. The purpose of these sensory systems on the robot is to detect obstacles and other robots. Also, a single processor (Z80-CPU) drives each sensor unit. In this paper, the robot mainly utilizes ultrasonic range finders for sonar-ring detection; and these range finders use enough time to avoid confusion based on multiple reflections. LOCISS works as a detector of limitation to the obstacle. LOCISS's obstacle detection range is from 0.1[m] to 0.4[m]. For distant range, the robot handles the distance information using ultrasonic range finders. On the other hand, for near range, LOCISS works to detect whether or not any obstacles are nearby. Later, we combine both ranges to obtain a hybrid external sensor system. Figure 8 shows the connection of the sensor controllers and CPU card inside of an omni-directional mobile robot.

COLLABORATIVE TELEOPERATION

We propose a collaborative teleoperation strategy utilizing the sensing ability of the target robot. In an ideal and effective human-machine collaborative tele-task execution, the task load should be well shared by both the operator and the robot. However, whereas human operators are generally able to determine an effective behavior and execute it in real time, robots do not yet posses a comparable degree of autonomy. A number of technical problems remain to be solved before high autonomous functioning of robots can be realized. In

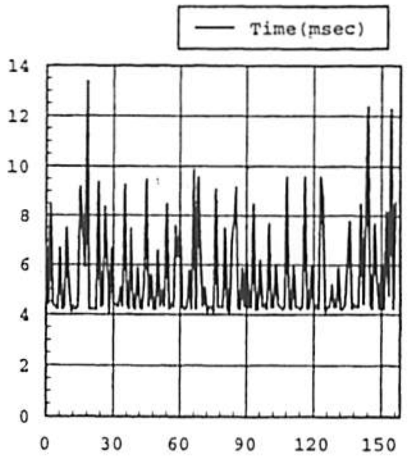


Figure 10 Random time delay on network.

the meantime, the robot should function as a local task assistant with its restricted autonomy. In our teleoperation system, the mobile robot has high sensing ability and the operator makes global decisions based on the images from a CCD camera affixed to the robot. Therefore, the operator must maneuver the mobile robot through an unknown environment based on limited information. However, the mobile robot has restricted autonomy and can manage local problems such as collision avoidance, local path planning, etc. The operator maneuvers the robot with a joystick and push-button controls, and supplies motion velocity values to the robot in the form of operation commands. Figure 9 shows the assignment of the robot's motion to the joystick. While the trigger button of the joystick is off, the joystick is in control of the moving direction. When the trigger button is on, the joystick manages the rotational direction of the robot and tilt motion of the CCD camera's. The operator can change the view angle of the robot. In this paper, we do not utilize pan-motion because it is similar to the robot's rotating motion. The camera motion function allows the camera to search in its vicinity and is independent of the robot's moving mode. The angle of depression of the joystick is directly proportional to the command velocity. The maximum velocity commands for motion of the robot and camera are 0.24 [m/sec] and 10 [deg/sec], respectively.

On the other hand, the robot also utilizes sensory information to make local decisions. Anderson and Donath (1990) proposed primitive behaviors for autonomous robots. However, their proposed behaviors only discussed autonomy of the mobile robot, and it is not clear how their proposed behaviors would function in an actual system. In this paper, we consider collision avoidance at a remote site. Collision avoidance is not a high intelligence task, but it is one of the most important and basic functions of a mobile robot. In realizing this task, the problem of time-delay is critical. Figure 10 shows the measured results of random time delay in the network. In the case of time delay, the operator could not effectively maneuver the mobile robot at a remote site. We consider how to improve the operation under such a time delay condition using the functions of the robot. In our system, the robot adjusts the velocity command from the operator as follows:

$$v_{comx} = v_{opx} - k(s)\mathcal{G}(||v_{opx}||, l_s)p_s \tag{1}$$

$$v_{comy} = v_{opy} - k(s)\mathcal{G}(||v_{opy}||, l_s)q_s \tag{2}$$

$$\omega_{com} = \omega_{op} \tag{3}$$

$$\mathcal{G}(v,h) = \begin{cases} 0 & \cdots \quad \alpha < h \\ \frac{v}{\alpha-\beta}(\alpha - h) & \cdots \quad 0 \le h \le \alpha \end{cases} \tag{4}$$

where

n : number of sensor
v_{comx} : actual velocity command for x-axis
v_{comy} : actual velocity command for y-axis
ω_{com} : actual velocity command for posture
v_{opx} : commanded velocity for x-axis
v_{opy} : commanded velocity for y-axis
ω_{op} : operator's velocity command for posture
l_i : measured distance to obstacle by i-th sensor
s : sensor number, which detects $\min(l_i)_{i=1,2,\cdots n}$
p_i, q_i : vectors for x-axis and y-axis of i-th sensor $p_i^2 + q_i^2 = 1$
α, β : threshold value for obstacles position ($\alpha > \beta$)

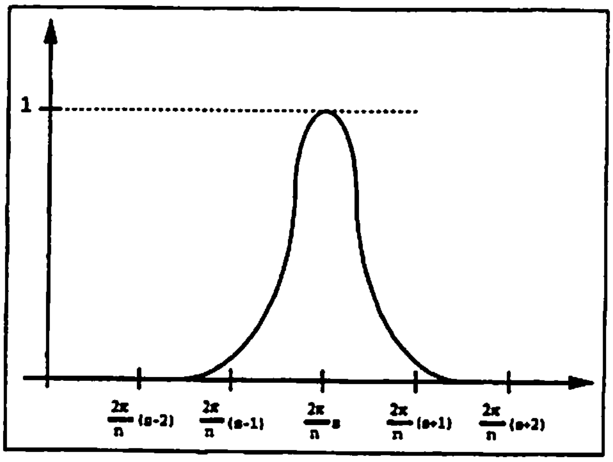


Figure 11 Gain function.

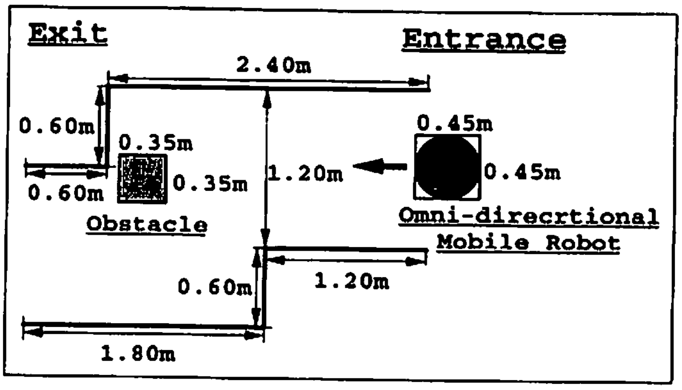


Figure 12 Environment for experiment.

The function $\mathcal{G}(.,.)$ expresses a virtual nonlinear spring characteristic based on the sensing result. It resists against the pushing direction but does not react against the pulling direction. For example, if the sensor detects an object behind the robot while the robot is moving forward, the robot increases its forward velocity. Figure 11 shows one example of $k(m)$ in such a case. p_i and q_i indicate the x-axis and y-axis values of unit direction vector respectively, where the robot's posture is Θ_c. In addition, they satisfy the condition: $p_i^2 + q_i^2 = 1$. In this case, n is 8 and the sensor units are set for the radiation-shaped on the robot. Here, the scalar value p_i and q_i are as follows:

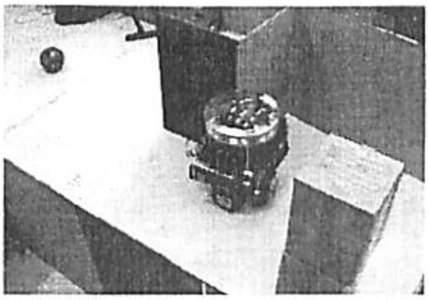
$$p_i = \cos\{\frac{\pi}{2} - \frac{\pi}{4}(i-1)\} \tag{5}$$

$$q_i = \sin\{\frac{\pi}{2} - \frac{\pi}{4}(i-1)\} \tag{6}$$

α and β determine the warning and the dangerous range for the robot, respectively. These variables are set as α and β is 1.0 [m] and 0.4 [m], respectively. The sensing ability and its area determine these parameters. In this case, the first threshold α depends on the ultrasonic range finder and the second threshold β depends on LOCISS. At distance closer than 0.3 [m], the ultrasonic range finder could not operate. Also, LOCISS is unable to determine the distance to the object, which the robot itself determines as 0.3 [m]. From 0.4 [m] to 0.3 [m], the above function works as a strong virtual spring characteristic. When the sensor units do not detect anything, the robot does not change the command from the operator. When $\min(l_i)_{i=1,2,\cdots n}$ is shorter than α and longer than β, the robot moves in the commanded direction in slow motion. And, when $\min(l_i)_{i=1,2,\cdots n}$ is β, the robot does not move. When $\min(l_i)_{i=1,2,\cdots n}$ is shorter than β, the robot resists the commanded direction. Sensing results does not influence the rotary motion command because the robot turns at its body center. These functions realize collision avoidance with the environment in a teleoperated system. Although they also could potentially result in deadlock, the operator should be able to anticipate such an unusual circumstance by means

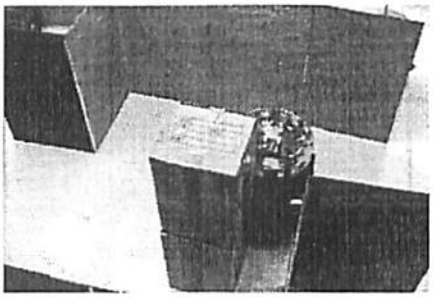
1. Start point.

2. Brush against the side wall.



3. Collision with the side wall.

4.



5. Collision with the obstacle.

6. Exit.

Figure 13 Experiment 1.

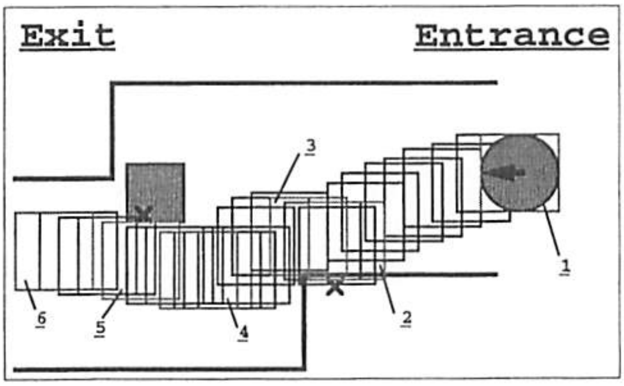
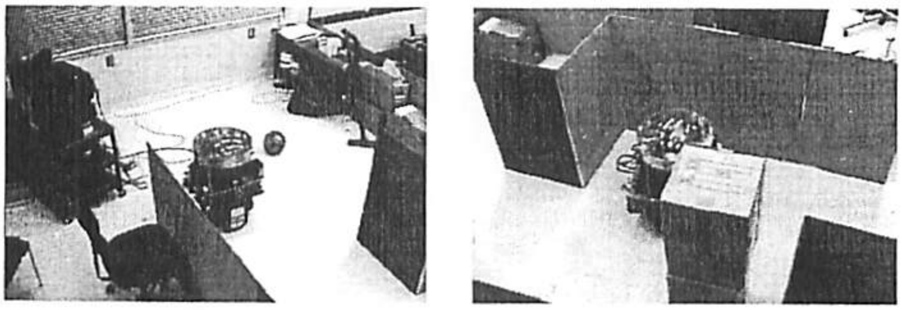


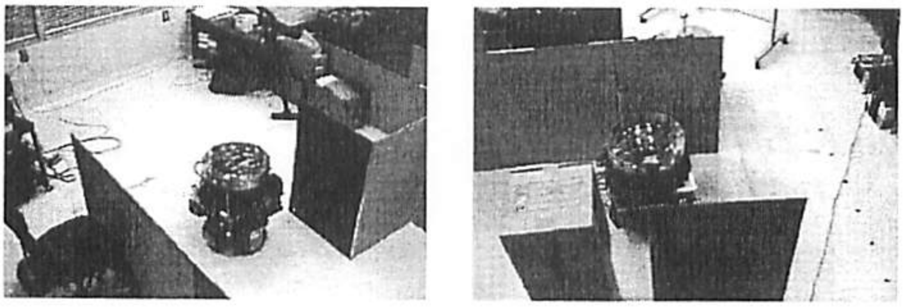
Figure 14 Trajectory of Experiment 1.

of the obtained images. As can be seen, these functions effectively realize a human-robot collaborative teleoperation system. For other tasks (for example, moving near to an object or wall), the robot must have other autonomous functions. Such functions would be simple to design as proposed functions, and the operator could change the mode with the interface of the operation site. In the next section, we discuss the results of our experimental trials using this system.



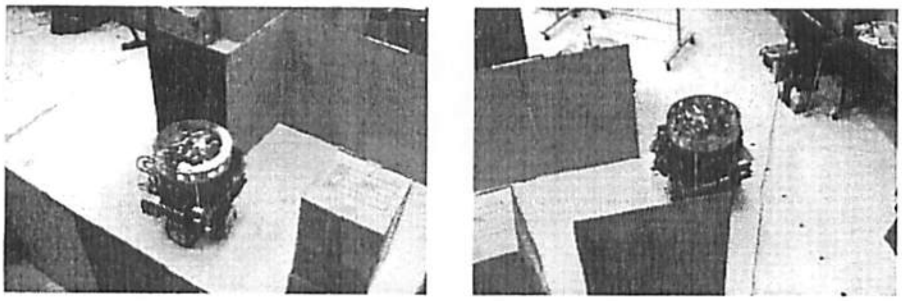
1. Start point.

4.



2.

5.



3.

6. Exit.

Figure 15 Experiment 2.

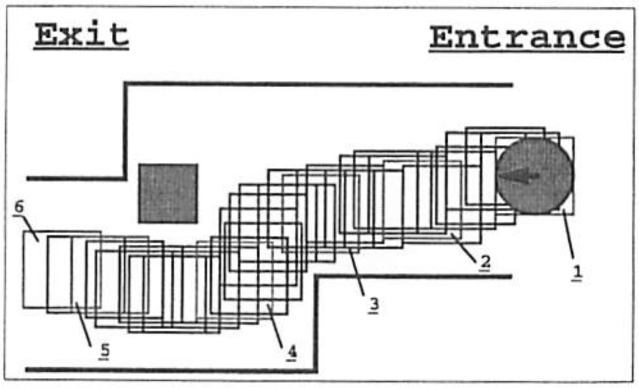


Figure 16 Trajectory of Experiment 2.

EXPERIMENTS

For the following experiments, we constructed the above proposed teleoperation system. Also, we conducted several narrow passage experiments at a remote site and in the environment shown in Figure 12. The environment consists of crank-type corridors with an obstacle blocking the exit. The operator did not know the environment, and the only information from the remote site consists of the images obtained during the experiment. An additional condition was that the operator was expected to maneuver the robot to pass through this narrow passage as quickly as possible. If the operator decided to search all the directions in the environment, he or she would be able to execute the task safely. However, this method requires a long time to execute the task and is not a particularly intelligent method. Moreover, it is not effective in the case of a real task execution. In this experiment, the operator had only 20 seconds to pass through the environment.

At first, we carried out the experiment using the conventional teleoperation. This meant that the operator maneuvered by means of only the feedback images. Passing through a narrow corridor is a difficult task under such a condition because the operator can not recognize the left-side, right-side or backward directions. Figure 13 shows the results of the experiment, and Figure 14 shows the trajectories. The numbers in Figure 14 indicate the event numbers from Figure 13. In Figure 14, the trajectory of the robot is plotted every 0.6 seconds and the cross marks indicate the collision points. This means that the operator can not maneuver the robot through a narrow environment using the forward direction images. Also, such collisions run the risk of destroying both the environment and the robot. However, the situation is slightly better than that with a conventional 4-wheel mobile robot. The operator took about 16 seconds to execute this task.

Next, we conducted the experiment using our proposed method. Since the robot has a sensing ability, it can determine its own actions. The results are shown in Figure 15, and the trajectories are shown in Figure 16. The numbers in Figure 16 indicate the event numbers from Figure 15. This figure also indicates the positions of each robot at every 0.6 [sec]. In this experiment, the operator spent about 19 seconds accomplishing this task. The robot did not collide with either the side walls or the obstacle. These experimental results indicate that the robot assigned the operator implicitly by means of its local sensory data. Our method improves teleoperation of the mobile robot. Moreover, the robot loitered in the environment, because it detected the possibility of collision with others and adjusted the command from the operator. Thus, although a slightly longer time was required for the task execution, but the execution could be considered safe for both the robot and the environment. And although negotiation of a narrow passage is still a simple or basic task, we are currently considering execution of a higher task through a network using a similar approach.

CONCLUSION

In this paper, we proposed a collaborative task execution system utilizing both an operator and an autonomous mobile robot. The proposed system is a type of conventional mobile robot teleoperation system. In this case, however, the robot had restricted autonomy which is used to solve local problems at the remote site. In the near future, we will execute some physical tasks through the network. The experimental results of our proposed system indicate the validity in such cases. The system solves the time delay problem in the network, and realizes easy teleoperation with only little information feedback. Moreover, we confirmed the improvement of the teleoperation system.

In this paper, we carried out teleoperation experiments for an autonomous omni-directional mobile robot. In our future work, we will investigate other systems with similar input devices. In addition, we will try to construct a Worldwide human-friendly teleoperation interface and a system featuring easy operation devices (Ishikawa et al., 1998; and Kawabata et al., 1997).

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