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Paper

A multi-robot teleoperation system utilizing the Internet

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Abstract—The paper describes a human interface system for multi-robot teleoperation using the WWW system. We discuss how to issue operation commands effectively through a human interface to let multiple robots work for plant maintenance tasks. Based on the discussions, an interface system utilizing WWW technology is constructed on the workstation on which our WWW server runs. When the WWW clients require tasks to the robot, the WWW server calls up the interface programs by using Common Gateway Interface scripts. It is confirmed that the operator can carry out inspection tasks from a distant place by teleoperating actual mobile robots using this system.

1. INTRODUCTION

The concept of distributed autonomous robotic systems (DARS) [1, 2] which are composed of multiple robotic agents has been attracting many researchers' and system designers' interests as one of the possible solutions which could realize flexible, robust and intelligent robotic systems. It is expected that high-level tasks can be executed by the DARS. Such tasks as emergency treatment, inspection of delicate damage, etc. have been usually carried out by human workers. In most of the research projects on DARS, it seems that the primary goal is to improve conventional system performance and to achieve autonomous task execution by the systems (e.g. [3–5]). However, it seems that it is not realistic for those robots to carry out all the high-level tasks autonomously by themselves. It is more feasible to build a system in which the human operator and the robots interact with each other and carry out the required tasks cooperatively. Recently, cooperation between a human operator and robots has been discussed from several standpoints in the field of human–machine systems (e.g. [6–9]). However, only few studies have focused on cooperation between a single operator and multiple robots or the development of the human interface to realize those cooperative works [10–12].

In this paper, we focus mainly on two problems on a human interface for multi-robot operation, i.e. how to lubricate cooperation between the human operator and the robots and how to utilize state-of-the-art Internet technology for teleoperation of such robotic systems. A prototype of the teleoperation system is developed and implemented on an actual testing platform which consists of multiple omni-directional mobile robots equipped with cameras. In the system, the operator can control multiple mobile robots through the human interface from a remote site by utilizing the WWW system.

2. CONCEPT OF THE SYSTEM

2.1. Overview

In this study, we develop a multi-robot teleoperation system for inspection tasks from a remote site considering the cooperation between the human operator and robots. We assume that a single operator maintains the plant by operating multiple mobile robots using the teleoperation system as shown in Fig. 1 [13]. Each robot carries a camera and inspects objects according to the operators requirements.

2.2. Teleoperation of multiple robots

A multi-robot teleoperation system which is composed of multiple robots, a human interface system and a human operator is illustrated in Fig. 2. In order to operate the multiple robots, it is necessary to obtain information on the robots, e.g. reports from the robots or the status of each robot, and to give commands to the robots through communication. Two directions of information flow should be established to enable this kind of interactive operation. One is the direction from the operator to the robots, in which operation commands are transmitted. The other is the reverse one, in which monitored information is passed (including the robots' status). When the operator simultaneously interacts with multiple robots in both directions described

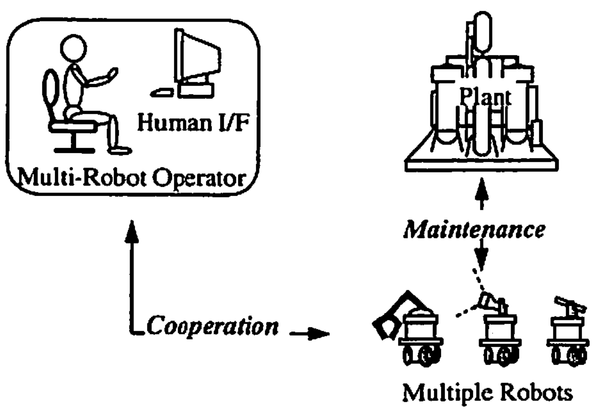


Figure 1. Concept of the plant maintenance system considering the cooperation between a human operator and multiple robots.

above, it is important to have sophisticated schemes to give commands to the robot and to monitor their behavior. Since we have already proposed a monitoring strategy to acquire the robots' status by eavesdropping communication among the robots [14, 15] and advantageous features of the strategy have been already proposed, here we discuss strategies for the other direction of information flow, i.e. operation of the multiple robots.

2.3. Usefulness of the Internet

In recent years, network technology has made considerable advances and has been widely spread in the world. An immense network provides various resources and services. The DARS can become a large-scale system which includes robots, sensors, human operators and other network resources by connecting them with each other (Fig. 3).

In order to realize a massively connected large-scale system based on the DARS concept, it is necessary to consider a flexible environment for networking many autonomous agents. It is, however, very difficult to develop a customized networking system. The Internet and the WWW system provide a flexible networking environment to build a human interface system for exchanging information through the Net. In this case, the robots in the system are regarded as terminal devices or autonomous agents which can interact physically with the real world, providing advantages as follows:

- The operator can control the robots by the same interface from any place connected to the network without constructing additional infrastructures for communication.

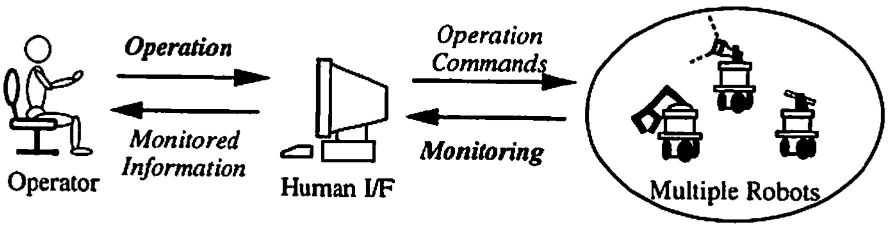


Figure 2. Schematic view of the multi-robot teleoperation system.

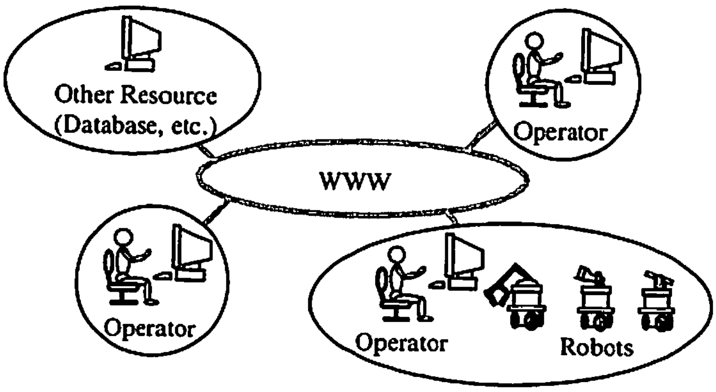


Figure 3. Concept of DARS on the Internet.

- The system can utilize the skills of the operator who is in a distant place.
- The operator is able to communicate with other operators through physical interaction of the robots.

3. ISSUES ON THE MULTI-ROBOT OPERATION SYSTEM

Multi-robot operation shows serious a difficulty in the case that a single operator manipulates the robots in the system simultaneously. To develop the multi-robot teleoperation system described above, more detailed issues should be addressed, e.g. (i) the roles or functions of each agent; (ii) interaction among the agents; and (iii) connection to the Internet. We discuss substantial issues illustrated in Fig. 4 in developing the system.

3.1. Position of the operator in the system

Because there is the case that the agents work autonomously and cooperate with other agents in the DARS, the relation between the operator and the system is looser than the centralized system. The operator can rely on the agent's autonomy to accomplish periodic, routine tasks. Hence, the operator does not always have to watch the system's status in the case of the decentralized system. While it is important to give autonomy to the agents, human involvement in the decentralized system is also important for the following reasons:

- It is simply impossible to provide full autonomy to each agent so that it does not require any intervention from outside.
- Because agents act in various manners, it is not so easy to analyze the system's current status automatically.
- When multiple agents cooperate with each other to carry out a task, human wisdom may be valuable, i.e. active cooperation between the operator and the agents will enhance the capabilities of the system.

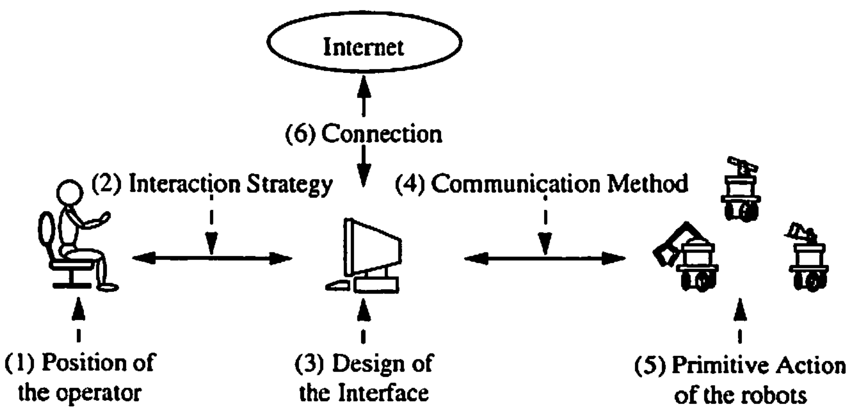


Figure 4. Issues in developing the multi-robot teleoperation system.

Therefore, the operator must be able to control all of the agents satisfactorily whenever he wants to. In our approach, the operator is regarded as one agent in the system so that the operator can contact agents and vice versa in the same manner through the interface system. We position the operator as a special agent which can explicitly control the other agents.

3.2. Interaction between the operator and the human interface

To operate the multi-robot under various situations, we define the operator's intervention as three commanding levels of operation as follows:

(1) **Task level.** The operator gives tasks to the robots by using abstract commands such as 'Execute task A', which are indicated by simple GUI (graphical user interface) operations such as menus and buttons. The human interface system and the robots understand the operator's requirements, and carry out the detailed calculation required for task execution.

(2) **Action level.** The operator gives robots' action to the robots as 'Move straight 1 [m]' or 'Go to the position (x, y)'. In this level, the robots or the human interface understand their action and execute the detailed calculation required for robot action.

(3) **Direct control level.** The operator controls robots' actuator and devices directly by sending signals or data to the robots. No detailed calculation is needed in this level.

Furthermore, operationality is important to be able to interact with various levels comfortably. The human interface should have several ways of inputs by the operator, e.g. buttons, menus, mouse clicks on graphics, command line input, etc. Therefore, we have decided to develop the human interface operated by a mouse and keyboard.

3.3. Design of the human interface

The human interface has to enable flexible communication between the operator and the robots in both direction discussed in Section 2. Therefore, the human interface must understand the requirement of the operator and tell the requirement to the robots clearly.

We designed the human interface system for multi-robot operation based on the discussion. The system is composed of five modules and two databases as shown in Fig. 5. The Presentation Interface Module accepts several commands given by the operator and presents the conditions of the robots' status. The commands are interpreted by the Operation Module into readable formats in the Communication Module. The Operation Module understands tasks from inputs of the operator and makes up for lack of information with which the operator can control the robots by taking information from the Operation Database. The Operation Database has information for operation; contents of maintenance tasks, cooperation strategies, map of plant, communication ID of robots in the system, etc. When the new data, robots or tasks, etc. are found during cooperation with the human operator or the robots, the data are renewed by

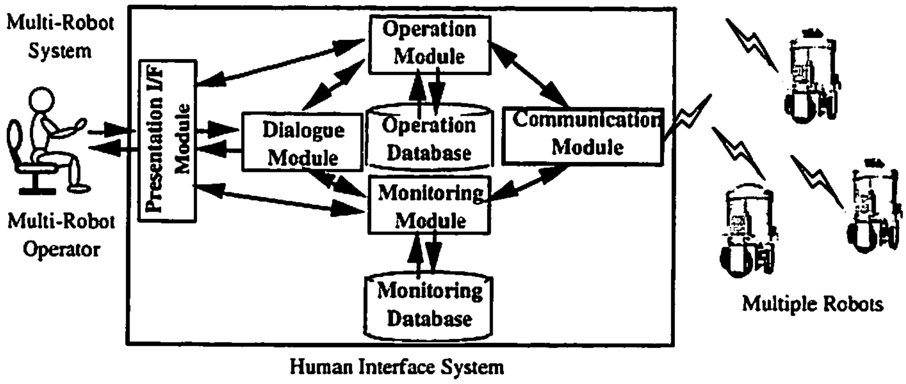


Figure 5. Configuration of the human interface system for DARS.

the Operation Module. The Monitoring Module gathers information in the system for monitoring purposes. It collects the information from the robots in the system using communication. The gathered information is indicated to the operator through the Presentation Interface Module and is preserved in the Monitoring Database. The Monitoring Database also preserves the monitoring strategies [14, 15]. In the case that the command input by the operator or monitored information gathered by the Monitoring Module has message-based contents, the Dialogue Module is responsible for coordinating interactive message exchange between the operator and robots. The Communication Module converts information into a uniform message protocol [16] to communicate with the robots. This module also converts the information from multiple robots and sends them to the target modules.

The operator is able to send commands to the robots by manipulating on-screen mechanisms, such as menus, buttons, etc. provided by the Presentation Interface Module. The Presentation Interface Module routes information to the Operation Module, the Dialog Module or the Monitoring Module according to the contents of the operator's action. The Dialog Module translates the operator's commands sent from the Presentation Interface Module into appropriate messages, and dispatches them to the corresponding module. When the robots need help of the operator, the interface system receives their messages and notifies the operator through the Presentation Interface Module.

3.4. Communication methods between the human interface and the robots

Considering various situations of tasks, a communication system which enables flexible communication among the agents is essential. Hence, the communication system and protocols have been developed to realize communication between multi-agents [16]. The agents can exchange information with each other by radio communication. Figure 6 shows a common communication format among the agents. The organization strategies using the communication system have also been developed to realize the cooperation among the agents [17]. The communication between the human interface and multi-robots conforms with these communication strategies.

In this system, all agents have unique IDs. Figure 7 shows a definition of an agent's ID. This ID consists of four separate fields; Group Field, Function Field,

To:	*Receiver's ID*
From:	*Sender's ID*
Control:	*Field for Message Control*
Class:	*Message Class*
Type:	*Message Type*
Message:	*Message Body*

Figure 6. Format of message protocol core.

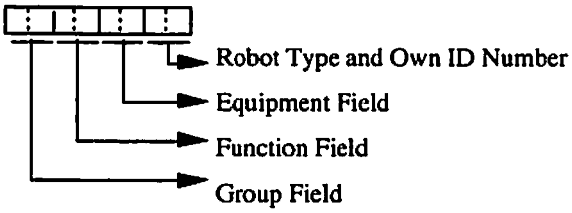


Figure 7. Definition of the robot.

Table 1.
Definition of each field

Fields	Definitions	
Group	G1–G*n*:	Group no. 1–*n*
	Ug:	*U*n*g*roup, etc.
Function	Vs:	*V*isual *S*ensing
	Tr:	*Tr*ansportation
	Hi:	*H*uman *I*nterface, etc.
Equipments	Cd:	*C*C*D* Camera
	Vc:	*VC*-C1 (a product name of camera)
	Fk:	*F*or*k* Lift
	Ne:	*N*o *E*quipmet, etc.
Agent's ID	O1–O*n*:	*O*mni-directional Mobile Robot no. 1–*n*
	W1–W*n*:	*W*orkstation no. 1–*n*
	P1–P*n*:	*P*ersonal Computer no. 1–*n*, etc.

Equipment Field, and Type and Number Field. The Group Field is used to identify the temporarily grouped agents. The Function Field represents the function of the agent to execute tasks by using its own equipment. The Equipment Field shows the kind of the device or device name which the agent carries. The Type and Number Field represents an agent type and its own unique ID number to identify the agent. Table 1 shows examples of each field. Table 2 shows the definition of an agent's ID in this system. For example, '**VsVcO1' represents 'omni-directional robot no. 1 which has visual sensing function, is equipped with a camera (VC-C1) and can carry out tasks using the camera'. The Operation Module can coordinate tasks or robot organization by using the robot's ID.

The information of the agent's function corresponding to primitive tasks is written in the Operation Database. The Operation Module can understand the functions of agents by referring to the Operation Database, 'which agent can execute the required tasks?'.

Table 2.
Initial definition of agents in the system

Agents	Initial IDs
Human Interface (Workstation)	UgHiNeW1
Omni-directional Mobile Robot no. 1	UgVsVcO1
Omni-directional Mobile Robot no. 2	UgVsVcO2
Fixed Camera (Personal Computer)	UgVsCdP1

In this communication system [16], the character '*' means the wild card. Therefore, the ID '**Vs****' represents all agents which have a visual sensing function. When the operator requires an observation task, the Operation Module broadcasts a task request message to the agents ID '**Vs****'. Since all of the agents know their own ID, the agents carrying a camera reply to the Operation Module. Thus, the agents which have the necessary functions for the specific tasks can be organized, grouped and coordinated.

3.5. Primitive actions of the robots

3.5.1. Omni-directional mobile robots. In order to realize flexible cooperative action, the omni-directional mobile robot have been already developed [18]. The control system is mounted on the robot. Batteries are also mounted on the robot for electrical devices and actuators. The robot can behave autonomously and independently. Each robot can communicate with each other through a radio Ethernet equipped on the robot.

They have cameras for inspection tasks and can obtain the observed images by using the image capturing board mounted on the robot. These images can be communicated through the Ethernet. Figure 8 shows the robots with cameras.

3.5.2. Cooperative actions for inspection tasks. It is important for the multiple robots to execute tasks autonomously according to the requirements of the operator. For example, in the case that malfunction occurs in the plant, the human operator has to correctly recognize the situation of the plant as if he is present at the actual malfunctioning point and is able to inspect it at sight. Concerning the formation of robots for such inspection tasks, coordination of a robot with a light source and another robot with a camera is one of the relevant examples which has been reported so far [19]. In order to achieve more flexible and effective operation of multiple robots, various formations should be prepared as one of the autonomous functions of the multi-robot system. Here, we propose the following formations for inspection tasks in the plant as a subset of such formations:

(a) *Multi-angle formation.* A dead angle always exists in a scene observed by a single robot. However, it is possible to compensate for the dead angle by scenes

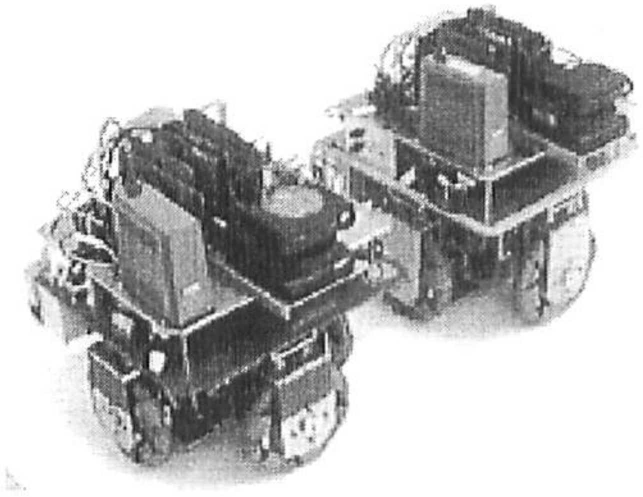


Figure 8. Omni-directional mobile robots.

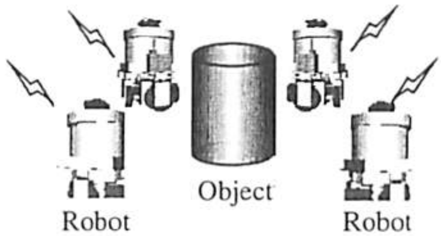


Figure 9. Multi-angle formation.

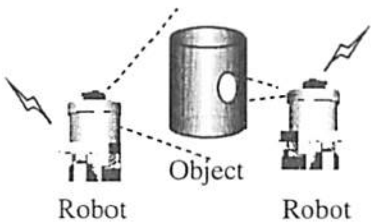


Figure 10. Multi-zoom formation.

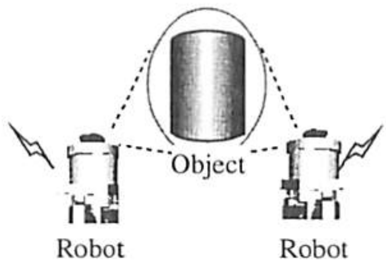


Figure 11. Binocular stereopsis formation.

observed from other robots. Dead-angle-free images can be displayed to the operator by this formation of robots (Fig. 9). It means that two or more robots cooperate with each other and they send the images observed from multi-angles simultaneously to the operator.

(b) *Multi-zoom formation.* Multi-zoom formation is a formation for simultaneous inspection in multiple views with different magnifications and resolutions. With this formation, the operator is able to have a detailed image of the working point while observing the overall situation around the object as shown in Fig. 10. It is a combination of macroscopic and microscopic views.

(c) *Binocular stereopsis formation.* When the operator makes a decision by visual information sent by the robots, the depth of information is essential to reconstruct the situation in the remote place. By this formation, the robots provide a stereoscope vision for the operator as shown in Fig. 11. When the formation can be used with a HMD, the system will provide VR sensation to the operator.

3.6. Connection to the Internet

In order to send operation commands to the robots and monitor them through the WWW browser, we connect the interface system to the Internet. In this system, the WWW browser is introduced as the Presentation Interface Module in Fig. 5. The Presentation Interface Module is constructed using Hyper Text Markup Language (HTML). The Operation Module, the Monitoring Module, the Dialogue Module and the Communication Module are composed of C language codes. These modules and the WWW server are installed on the same workstation. Programs for the modules are invoked by the WWW server using CGI (Common Gateway Interface) scripts.

4. A PROTOTYPE OF A HUMAN INTERFACE SYSTEM USING WWW SYSTEM

We have developed a prototype system based on the structure presented above. Figure 12 illustrates the prototype system connected to the Internet. The system enables the operator to send operation commands to the robots and monitor them through the WWW browser. Then, we designed the window of the prototype of the Presentation Interface Module. Figure 13 shows the Presentation Interface Module which is constructed using HTML. The window is divided into three columns and each column is divided into two frames.

Frames (A) and (B) in the top column are the frames for presentation of images. Frame (A) shows images sent by robots. The operator can inspect the object in a remote place by looking at these images. Frame (B) shows a birds eye view from a fixed camera agent. The operator can ascertain the general status of tasks by looking this image.

Frames (C) and (D) in the middle column are the frames which enable the operator to send commands to the robots for multi-robot operation. This column corresponds to the operation levels described in Section 3.2. A map in frame (C) shows the working environment of the robots. The area nos. 4, 6 and 14 on the map in frame (C) show the task objects of the robots. Other areas show the space where the robots can move to. When the operator clicks the object, the Operation Module understands that the

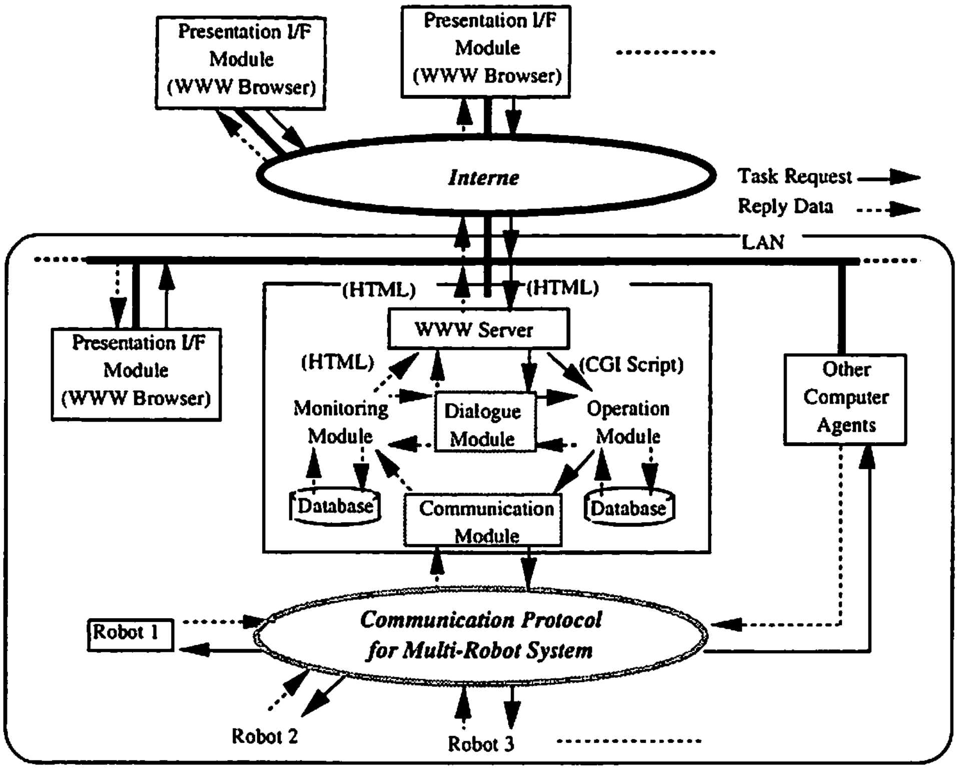


Figure 12. Human interface architecture through the Internet.

operator sends a Task Level command as 'Inspect object no. 4' and send the Task Level command to the robots. In the case that the operator clicks other areas on the map, the Operation Module understands that the operator sends an Action Level command such as 'Move to area no. 10', then sends the Action Level command to the robots. Frame (D) corresponds to the Direct Control Level operation. The operator can control the robots directly by using this panel.

Frames (E) and (F) in the bottom column are the frames for the presentation of the robots' status. Frame (E) is a dialogue window which can exchange the message between the operator and the robots. Frame (F) shows a robots' status when the operator pushes the button of the robot's name.

Each module and the WWW server are installed on the same workstation.

The system's execution scenario is as follows:

(1) At first, the robots wait for the commands from the operator at the initial position. The operator grasps the system's status as an environment and robots by looking at frames (B) and (F).

(2) In the case that the operator needs to inspect the objects by judging from the system's status, he inputs task commands by selecting items in the menu, pushing a button or clicking the object on the clickable map of the HTML.

(3) The WWW server accepts the operator's command and invokes the Operation Module Program by CGI scripts. Then, the scripts send task contents and object information to the Operation Module.

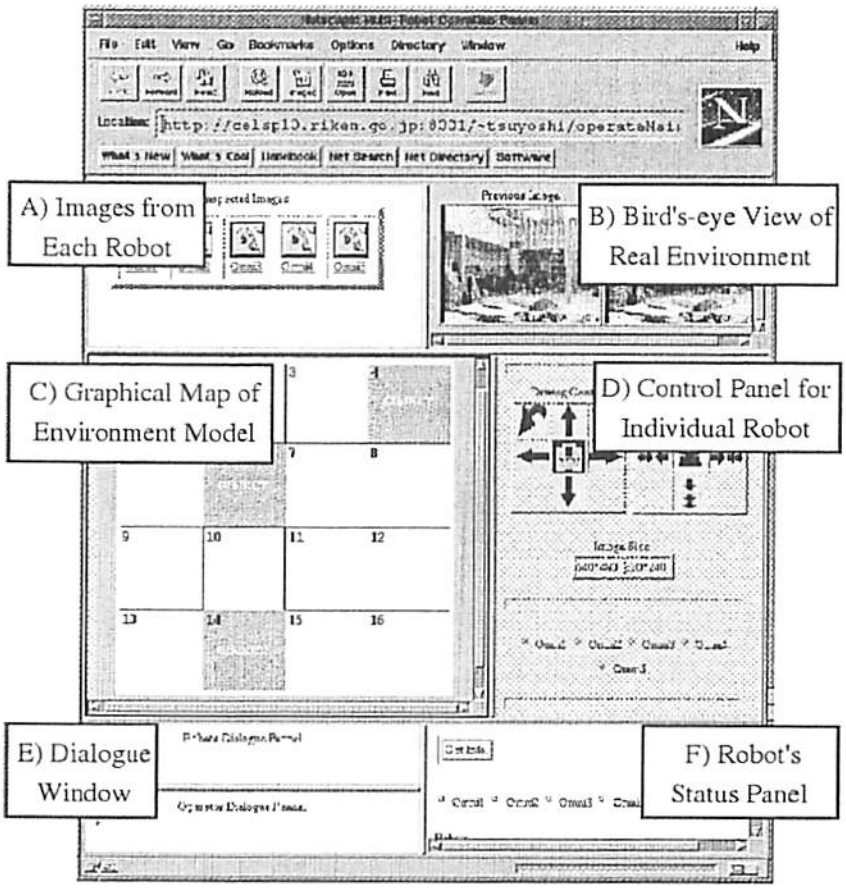


Figure 13. A sample of the presentation interface.

(4) Consulting the operation database in which a table indicating the relationship between known tasks and robot functions exists, the Operation Module determines necessary facilities and operations for the given task, and allocates robots available in the working place. With this complete set of information, the module contacts the Communication Module.

(5) The Communication Module transmits commands to robots via wireless LAN.

(6) The robots reply to the task request, then the Operation Module negotiates with robots through the Communication Module in order to specify the robots that execute the task.

(7) After the robots complete the tasks, they send the data (own positions, images and/or messages) to the Monitoring Module through the Communication Module. Then, they wait for the next commands.

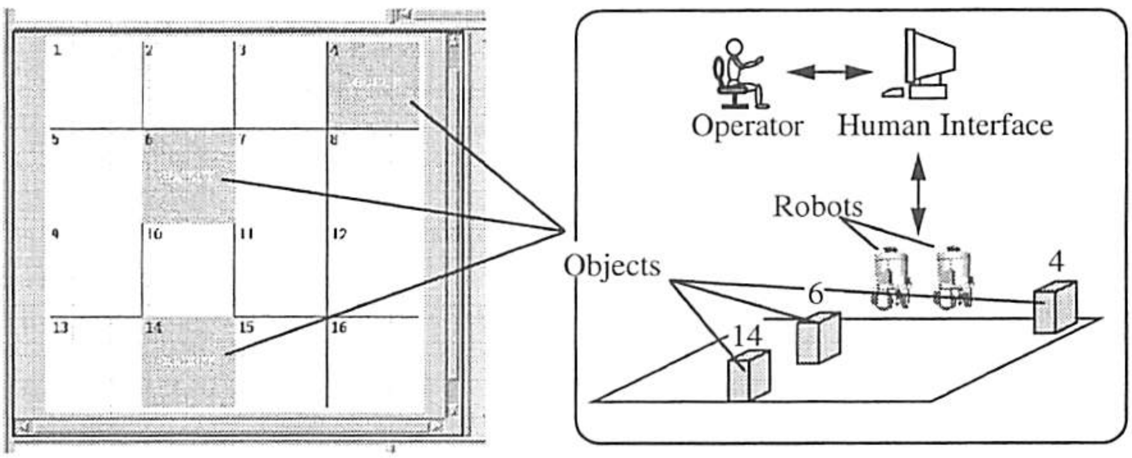
(8) The Monitoring Module saves these execution data to the Monitoring Database and writes the data to a HTML format file so that the WWW server can read it.

(9) Finally, the data in HTML format are called up by the WWW server and presented in the Presentation Interface Module (the WWW browser). If the robots are busy or send back no replies, the Monitoring Module sends the messages such as 'Cannot execute task, because ...'.

5. AN EXAMINATION OF TELEOPERATION

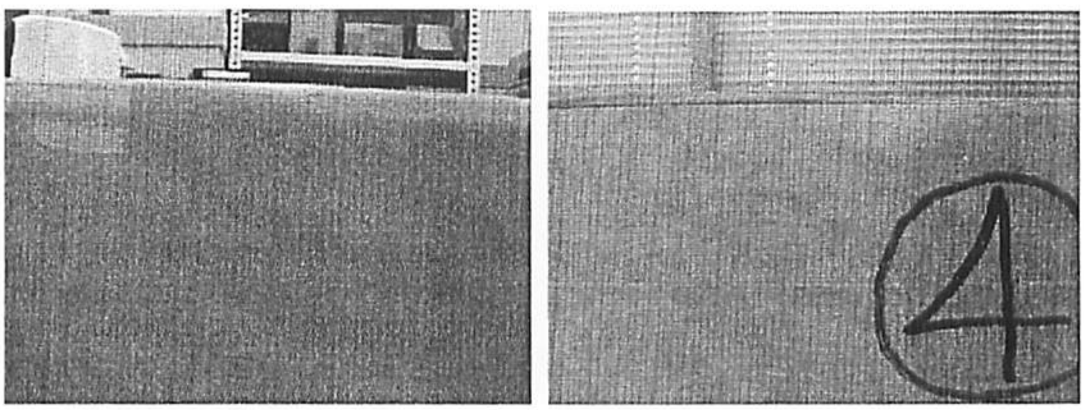
In an actual inspection task in a plant, we observed objects by teleoperating multi-robots. We executed an observation task by giving commands to the robots by clicking an object on the environment map shown in Fig. 14. The operator required the robots to observe objects 4, 6 and 14, sequentially. The observation can be achieved using the formations introduced in Section 3.

Figure 15 shows the images sent from the robots. The robots took these images from different directions to each other. The images are shown to the operator through the WWW browser. Figure 16 shows trajectories of robots which observe objects using the Multi-Angle Formation according to the operator's request. This result shows that the operator can control the robots and observe an object in a distant place through the WWW browser. Figure 17 shows a part of the communication logs between the WWW server and the robots. The WWW server required an observation task to the



(a) Operation Map on the Browser (b) Experimental Environment

Figure 14. An example of the operation map.



(a) (b)

Figure 15. Images from robots: (a) image from Robot 1; (b) image from Robot 2.

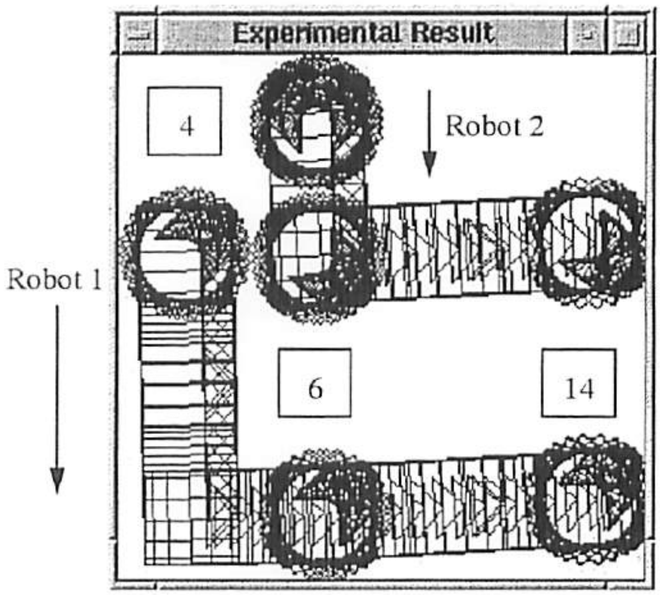


Figure 16. Trajectories of robots using multi-angle formation.

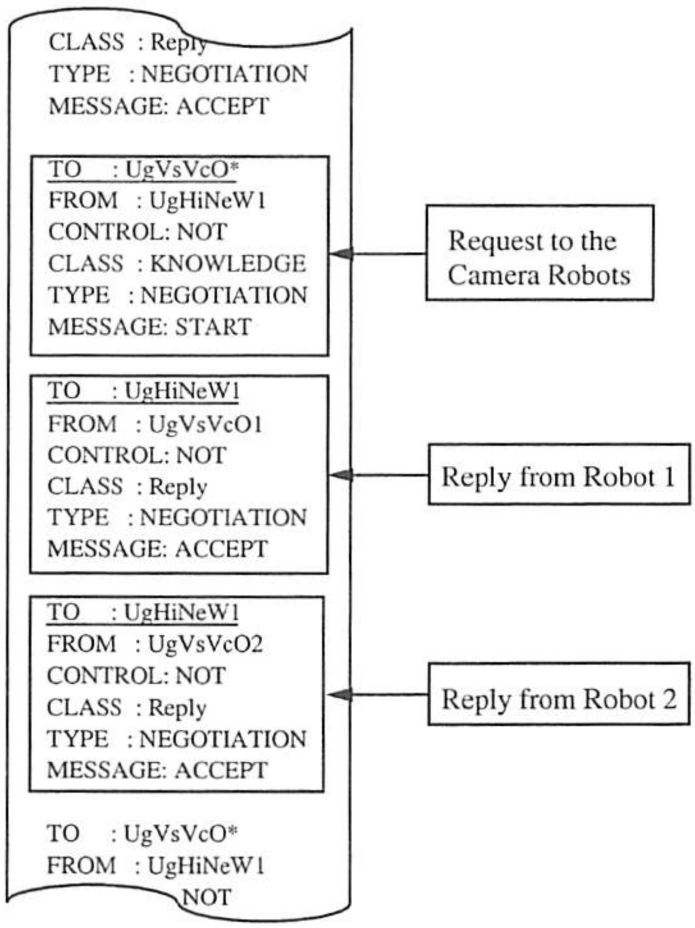


Figure 17. Part of a communication log between the human interface and the robots.

robots' ID of 'UgVsVcO*'. Robot 1 and 2 which have cameras replied to the WWW server.

6. CONCLUSION

In this paper, a framework of the human interface system for teleoperation of multiple robots was discussed. The prototype of the teleoperation system was constructed utilizing the WWW system as a developing and operating environment. The system can be used for teleoperation experiments via the Internet to investigate various issues related to multiple robot operation by a single remote operator through an information pathway with dynamically changing capacities.

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