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Tele-operated Control of an Autonomous Mobile Robot Using a Virtual Force-reflection

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Abstract

In this paper, the relationship between a slave robot and the uncertain remote environment is modeled as the impedance to generate the virtual force to feed back to the operator. For the control of a tele-operated mobile robot equipped with camera, the tele-operated mobile robot take pictures of remote environment and sends the visual information back to the operator over the Internet. Because of the limitation of communication bandwidth and narrow view-angles of camera, it is not possible to watch the environment clearly, especially shadow and curved areas. To overcome this problem, the virtual force is generated according to both the distance between the obstacle and robot and the approaching velocity of the obstacle. This virtual force is transferred back to the master over the Internet and the master(two degrees of freedom joystick), which can generate force, enables a human operator to estimate the position of obstacle in the remote environment. By holding this master, in spite of limited visual information, the operator can feel the spatial sense against the remote environment. This force reflection improves the performance of a tele-operated mobile robot significantly.

Key words : Internet based control, Virtual impedance method, Teleoperation, force reflection, Tele-autonomous.

1. Introduction

In the field of teleoperation systems, telepresence is its ultimate purpose. The ideal situation is that information from a remote site and the working environment is transferred to a human operator. The general method of implementing such systems is to feed back the visual information of the remote environment. However, this method is not sufficient in some fields. In telesurgery systems, which are an application of teleoperation, it is required to gain other information such as contact force between the slave robot and objects.

In teleoperation systems the bilateral control method is a form of teleoperation to transfer information from slave site to master site as we transfer information from master site to slave site. It is used to control contact force and position or velocity of the tele-operated robot. And it is commonly called teleoperation provided with force reflection. Generally, the inputs are velocity(or contact force of operator) and the outputs are the contact force of the tele-operated robot in bilateral control[1,2,3]. In its previous study, the major issues are to provide the human operator with the more accurate control performance by using tactile information in addition to visual information as the contact force between ARM robot and the remote environment is exactly retrieved to the human operator[4].

Therefore the study of tele-operated mobile robots, which deals with contact between mobile robots and objects, is rarely found except several studies which deal with bilateral control using force reflection [5,6,7].

In this paper, we used both tele-operated mobile robots in remote environments and a two degrees of freedom joystick to perform internet based control. We also represented the information about mobile robots and the environment as virtual force, and studied the bilateral control which fed it back to the human operator.

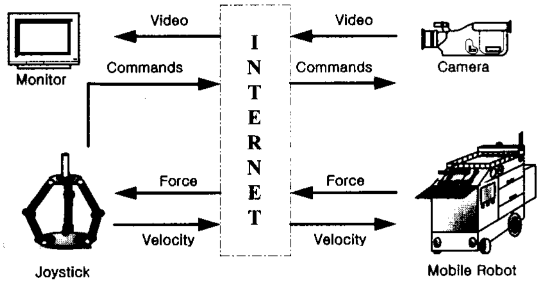


Fig. 1. Block diagram of the system used in this study

As seen in Figure.1, what we call master-slave systems consist of operator, joystick, communication block and slave robot. To transfer the information from a slave robot in a remote environment, such as the distance between a mobile robot and an obstacle, and approaching velocity to a human operator, we generated force using the motor attached to each axis of the joystick.

In spite of the limited situation, namely, transmission delay of its channel, limited bandwidth, and camera trouble, the operator can recognize the distance between the mobile robot moving according to the force felt from the joystick and objects not seen in the visual display system.

In this study, using Virtual Mass-Spring-Damper Model, we have modeled the relation between the mobile robot and the objects in the remote environment as impedance.

2. Kinematics of mobile robot

The state of mobile robot is represented as the vector $\mathbf{p} = [x \quad y \quad \theta]^T$ which has the position and the direction like the Fig. 1. In general, the motion of the mobile robot is modeled Eq.(1), (2) which have the translation velocity and the angular velocity.[8]

$$u = \frac{1}{2}(v_R + v_L) \tag{1}$$

$$\omega = \frac{1}{L}(v_R - v_L) \tag{2}$$

Here, v_R, v_L is the right and left velocity.
The L is distance between two wheels. The velocity $\dot{p}$ is represented by Eq.(3) using the Jacobian matrix.

$$\dot{p} = J(p)\dot{q}$$
$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ \omega \end{bmatrix} \tag{3}$$

The position vector p is the integration form of Eq.(3) like Eq.(4).

$$p = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \\ \theta_0 \end{bmatrix} + \begin{bmatrix} \int u(\tau)\cos(\theta(\tau))d\tau \\ \int u(\tau)\sin(\theta(\tau))d\tau \\ \int \omega(\tau)d\tau \end{bmatrix} \tag{4}$$

Fig. 3 shows the configuration of the mobile robot and Ultrasonic Sensors to acquire distance data are arranged as in Fig. 4.

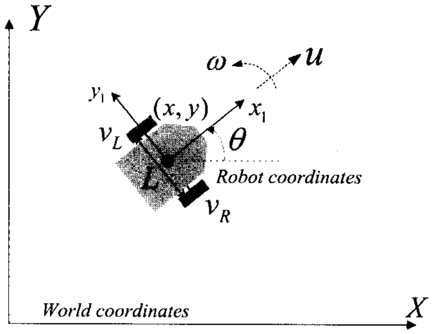


Fig. 2. Model of a mobile robot.

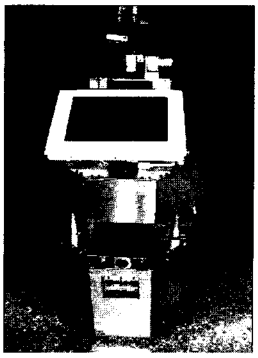


Fig. 3. The Configuration of Mobile Robot

3. Path planning of mobile robot and Obstacle avoidance algorithm

Impedance control is the algorithm that adjusts the position to the force feed back and maintains constant force, modeling interconnections between uncertain environments and the robot as impedance[9].

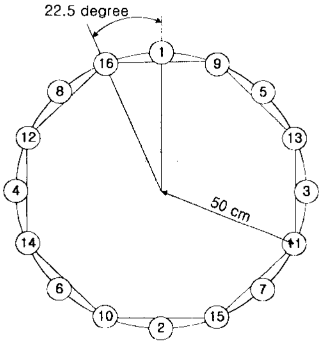


Fig. 4. The arrangement of Ultrasonic Sensors

The Virtual Impedance method[10,11] is that the general impedance algorithm is applied to the travel of the mobile robot and collision avoidance field. As seen in Fig.5, the virtual impedance method is a form of generating virtual force according to the information from distance and velocity, the modeling robot and a reference point, and relation between the robot and the obstacles as a spring and a damper. This method is generally used as LAP(Local Avoidance Planner). That is to say, when GPP(Global Path Planner) generates trajectory $X(t)$, $\dot{X}(t)$ consists of a reference point, and we can calculate acceleration $\ddot{x}$ of the robot allowing deviation from the given trajectory to generate virtual force according to the distance between the robot and an object at the given reference point.

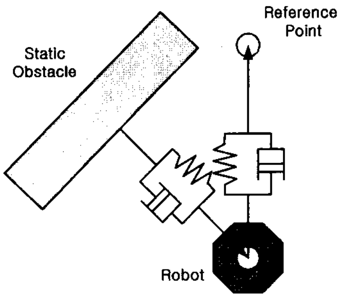


Fig. 5. The Virtual Mass-Spring-Damper Model

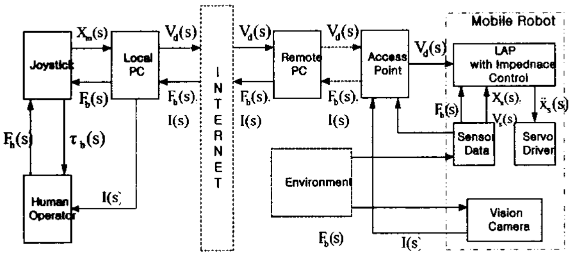


Fig. 6. The total system architecture

4. System Model

In this paper, master-slave systems consist of a human operator, a master joystick, a communication block and a slave robot, as shown in Fig. 6.

4.1 Master(Joystick) System Model

A human operator can feel virtual force generated between a tele-operated mobile robot and the remote environment, and a two degrees of freedom joystick is implemented to prescribe to a robot. Fig.7 shows the block diagram of the joystick system implemented in this paper. To control the joystick, the joystick controller is designed using an 80C196KC micro-processor. This retrieves the force at the joystick based upon the force values F_x and F_y which are sent from the PC to the operator For this purpose, it drives two axial motors by sending out PWM(Pulse Width Modulation) outputs corresponding to the F_x and F_y. L298N DC motor drives are used to amplify the power.

The position of the joystick is measured using potentiometers attached at each axis. The voltage measured by the potentiometers is transformed to 10 bits digital data by an A/D(Analog to Digital) converter, which is fed to the joystick controller as inputs. To measure the force at the joystick held by the operator, a current sensor is used. The current is changed to the voltage by a 2 Ω resister and an LPF(Low Pass Filter), and the resultant voltage is transformed to 10 bits digital data by an A/D converter, which is also fed to the joystick controller as control inputs.

The whole system's configuration is seen in Fig.7. When the operator gives a force F_h to the joystick, from Eq.(5) the position coordinates of the joystick are changed to a degree of displacement X_m. as shown in Fig.8. Such a displacement X_m generates the desired velocity V_d by the following equation.

$$V_d(s) = K_m \cdot X_m(s) \tag{5}$$

where, $X_m = \begin{bmatrix} X_{mx} \\ X_{my} \end{bmatrix}$, $V_d = \dot{X}_d = \begin{bmatrix} V_{dx} \\ V_{dy} \end{bmatrix}$, and K_m is a scaling constant. The desired velocity of the robot $V_d\ (= \dot{X}_d)$ in the reference Point X_d is transferred to LAP of the robot in the remote site.

4.2 Motion Planning Using Virtual Impedance Model

As seen in Fig.9, the following equation is the dynamic equation defined by Virtual Impedance.

$$\ddot{x}_s(s) = \frac{1}{M_s}\{F_m(s) + \sum_{i_{od}=0}^{n_{od}} F_{od}(s) + \sum_{i_{os}=0}^{n_{os}} F_{os}(s)\} \tag{6}$$

In Eq.(7), F_m is the virtual force generated between the current position of the robot $x(s)$ and the reference point generated by the operator in the master site. F_m is generated by the following equation.

$$\begin{aligned} F_m(s) &= K_{s,d}(X_{s,d}(s)) + D_{s,d}(\dot{X}_{r,s}(s)) \\ &= -K_{s,d}(x_s - X_d) - D_{s,d}(\dot{x}_s - \dot{X}_d) \end{aligned} \tag{7}$$

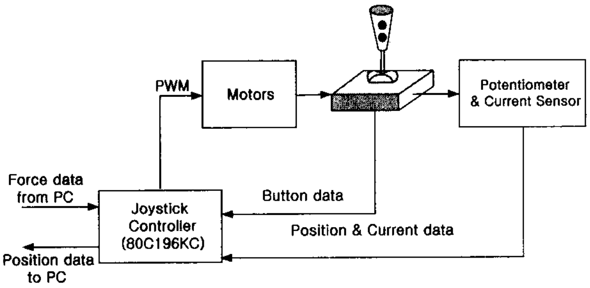


Fig. 7. Block diagram of joystick system

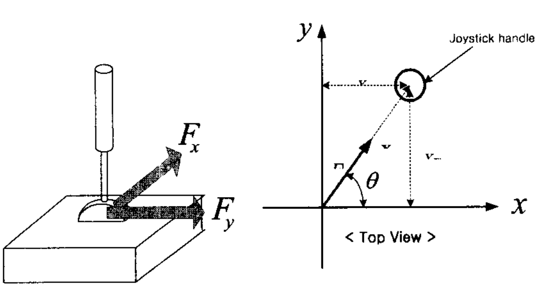


Fig. 8. Joystick axis and coordinates

Where, $K_{s,d}$ is the spring constant between the current position of the robot $x_s(s)$ and the reference point $X_d(s)$,

$D_{s,d}$ is the damper constant between the current velocity of the robot $\dot{x}_s(s)$ and the velocity at the reference point $\dot{X}(s)$.

F_{od} and F_{os} are virtual repulsive forces between the current position of the robot and the respective moving and static objects. The summation of virtual repulsive force is expressed as Eq.(9).

$$F_o(s) = K_{o,s}(X_{o,s}(s)) + D_{o,s}(\dot{X}_{o,s}(s))$$
$$= \begin{cases} \sum_{i=0}^{n} \{K_{o,s}(\rho_0 - d_i)\frac{x_s - x_{oi}}{d_i} + D_{o,s}(\dot{d}_i)\} \\ \qquad , \ when\ \|x_s - x_{oi}\| < \rho_0 \\ 0 \qquad , \ otherwise \end{cases} \tag{8}$$

Where, $K_{o,s}$ is a spring constant according to the distance between a robot and an obstacle, $D_{o,s}$ is a damping constant according to the approaching velocity of the obstacle, ρ_o is a measurable range of the ultrasonic sensor, and $d_i = \|x_s - x_{oi}\|$.

In Eq.(6), the virtual mass M_s does not represent the real "mass" of the robot but the relative unchangeability of the robot trajectory. In a sense, a robot with a larger M has a higher priority

4.3 Virtual Force Feedback

In Eq.(6), the virtual force F_b feed back to the operator is represented in the following equation.

As a result, a data feed back $F_b(= F_m - F_s)$ is the difference between a command value F_m (or V_m) of the operator and the real affected force F_s (or V_s) to the robot. In Eq.(10), F_b, which is generated from a mobile robot in a remote site, is transferred to the operator in the master site.

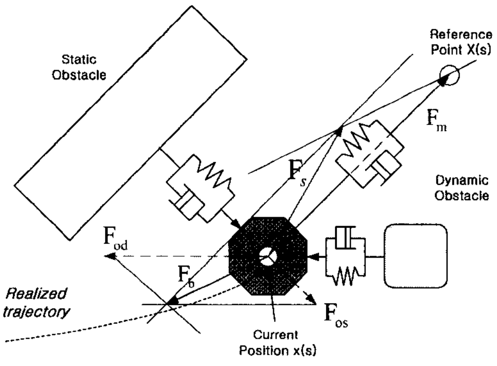


Fig. 9. Motion Planning with virtual impedance

$$F_b = \{\sum_{i_{od}=0}^{n_{od}} F_{od}(s) + \sum_{i_{os}=0}^{n_{os}} F_{os}(s)\} \tag{9}$$

$$\tau_b(s) = sat(K_b \cdot F_b(s)) \tag{10}$$

$$sat(x) = \begin{cases} x & , \ if\ |x| \le x_{\max} \\ \mathrm{sgn}(x) \cdot x_{\max} & , \ otherwise \end{cases}$$

Where, K_b is the constant of force feedback gain.

In spite of the limited situation of visual information such as transmission delay of its channel, limitation of bandwidth, and camera trouble, the operator can recognize the distance between the robot moving according to the force τ_b felt from the joystick and the objects not seen in the visual display system.

5. Simulation and Experimental Results

5.1 simulation

In this paper the virtual impedance method described in part 3 and part 4.1 is used for the teleautonomous motion planning of the tele-operated mobile robot.

Before the experiment, three kinds of simulations have been performed to verify the validity of the virtual impedance method. Fig.10 simulation **I** shows the variation of the robot's motion according to the changing constant.

Case I : $K_{s,d} = 2, D_{s,d} = 10, K_{o,s} = 2, D_{o,s} = 10, and\ M_s = 10$.
Case II : $K_{s,d} = 4, D_{s,d} = 10, K_{o,s} = 2, D_{o,s} = 10, and\ M_s = 10$.
Case III : $K_{s,d} = 2, D_{s,d} = 10, K_{o,s} = 2, D_{o,s} = 10, and\ M_s = 2$.
Case VI : $K_{s,d} = 2, D_{s,d} = 10, K_{o,s} = 5, D_{o,s} = 20, and\ M_s = 10$.

Especially, as shown in Fig.10 Case III the extremely small virtual mass of the robot reduces its control performance. The simulation result of Fig.11-(a) shows the motion planning of the mobile robot from a static obstacle. Fig.11-(b) shows the velocity of the mobile robot, the distance between a mobile robot and an obstacle, and the virtual force.

Fig.12 is the simulation result of the dynamic obstacle as performed the same method in Fig.11

From the simulation results as seen in Fig.11 and Fig.12, the greatest virtual force is generated when the danger of collision with an obstacle is at the highest moment.

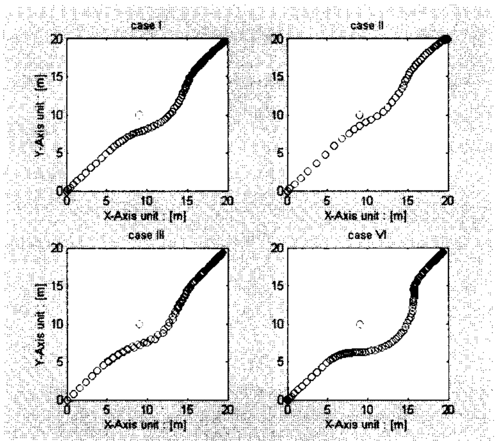
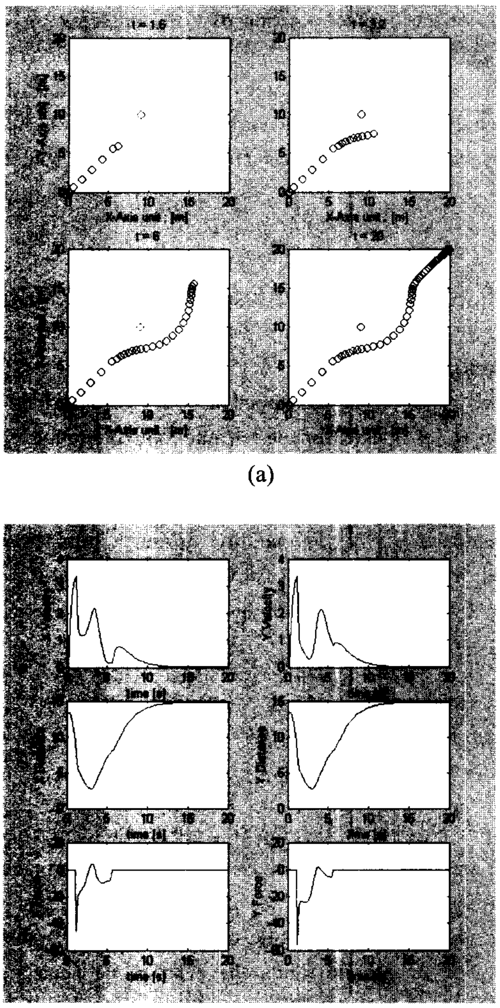


Fig. 10. Simulation **I**



(a)

(b)

Fig. 11. Simulation II - Static Obstacle
(where, 2 $K_{s,d}=2,\ D_{s,d}=10,\ K_{o,s}=2,\ D_{o,s}=10,\ and\ M_s=10$)

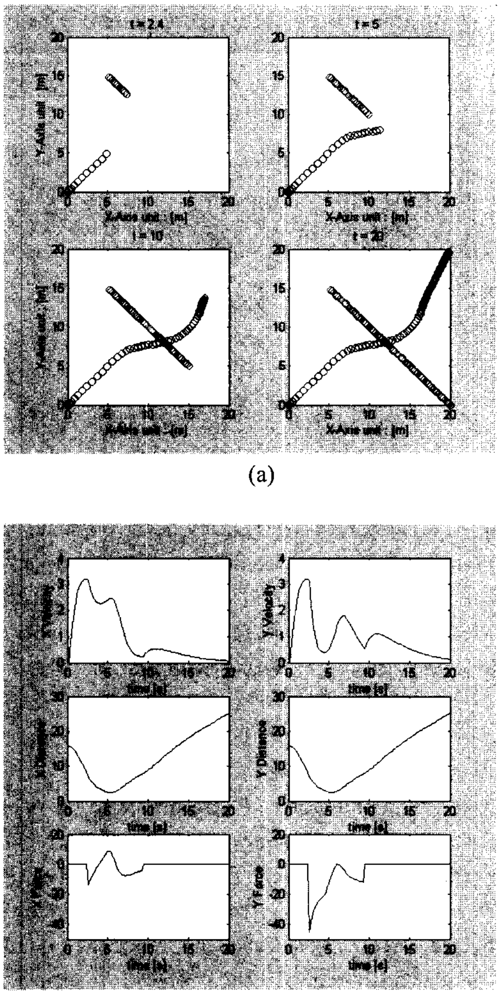
5.2 experimental results

In this paper the operator in the master site can control the robot in the remote environment by using the client program in Fig.13 over the Internet.

The operator can recognize the remote environment with the visual information. However, as seen in Fig.13, we cannot recognize the situation of the remote environment, such as narrow view-angles of camera, the limitation of communication bandwidth, and lack of lighting.

Fig.14 shows our experimental environment for tele-autonomous motion planning. Fig.15 shows the sampling time and the control architecture implemented in this paper. Where, $T_3=T_2=300[ms]$ and $T_1=50[ms]$.

We have proposed the virtual impedance method for the trajectory tracking and real-time obstacle avoidance in the teleoperation. With this method, we have performed the tele-autonomous motion planning of the tele-operated mobile robot as shown in Fig.16.



(a)

(b)

Fig. 12. Simulation III - Dynamic Obstacle
(where, $K_{s,d}=2,\ D_{s,d}=10,\ K_{o,s}=2,\ D_{o,s}=10,\ and\ M_s=10$)

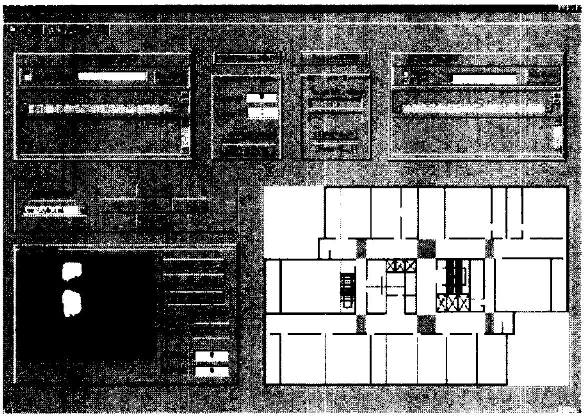


Fig. 13. A user interface for tele-operated mobile robot over the Internet

As a result, we showed that the method proposed in this paper is valid.

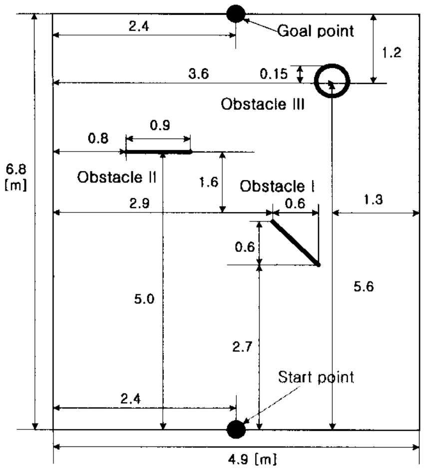


Fig. 14. Our Experimental environment

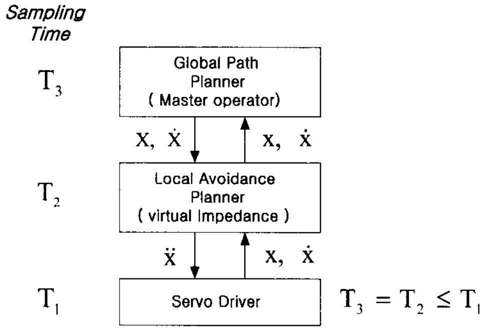


Fig. 15. Sampling Times and the control structure of our Teleoperation system

6. Conclusions

In this paper, the virtual impedance method that enables a real-time planning to follow the generated trajectory while avoiding obstacles in the teleoperation is proposed. In the virtual impedance method, the virtual force is generated according to both the distance between the obstacle and robot and the approaching velocity of the obstacle. This virtual force is reflected to the operator who is holding the master which converts the force data transferred over the Internet to physical quantity.

It is shown that the operator could estimate the position of obtacle in the remote environment by virtual force regenerated from the force reflection joystick, experimentally. In spite of the limited visual information, the operator can feel the spatial sense against the remote environment by using the proposed method. Therefore the tele-operated mobile robot can perform highly skillful tasks with the operator's supervision who is monitoring and feeling the unstructured environment.

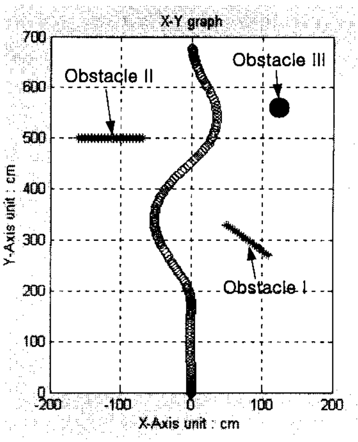


Fig. 16. Experimental Results of our Teleoperation system

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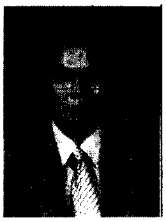

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