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Implementation of a Remote Peg-in-Hole Operation using a Two Degrees of Freedom Force-Reflective Joystick

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Abstract : A virtual reality system is implemented for the operator supervising a robot's operation at a remote site. For this implementation, a two D.O.F force-reflective joystick is designed to reflect the force/torque measured at the end of robotic manipulator and to generate the motion command for the robot by the operator using this joystick. In addition, the visual information that is captured by a CCD camera, is transmitted to the remote operator and is displayed on a CRT monitor. The operator who is holding the force reflective joystick and watching the CRT monitor can resolve unexpected problems that the robot confronts with. That is, the robot performs the tasks autonomously unless it confronts with unexpected events that can be resolved by only the operator. To demonstrate the feasibility of this system, a remote peg-in-hole operation is implemented and the experimental data are shown.

Keywords : tele-operation, force-reflective joystick, peg-in-hole, autonomous/supervisory, force/torque

I. Introduction

Robotic manipulators have become increasingly important in the field of flexible automation where operators are supervisoring the automated task procedure. Also human operators should relingquish the tasks which are subjected to nuclear weapon, space, underwater, and dangerous places to the robots[1,3]. Therefore, the robot tasks are not limited to the simple repeative tasks following a pre-determined trajectory or sequence.

The robots which are required to perform various tasks in hazardous places, may confront unexpected events which can not be resolved by using the knowledge base kept in the robot controller. To overcome the extraordinary situations, human brains need to be included in the control loop. As the result, the necessity of remote control is emerged recently[7].

For the remote operation, the changes of working environment should be closely watched all the time either by the controller or by the operator. Conventional industrial robots which perform repeative tasks are not applicable any longer for this tele-operation. Therefore, the development of an intelligent robot which adapts itself actively to the changes of working condition has been required. In addition, researches on the virtual-reality based remote control are getting interests, where the information on the working robot and environment needs to be sent to the remote operator in terms of force and vision information[2].

A remote control system consists of a master and a slave which follows the command sent by the master. At the initial stage of tele-operation, the interface between the master and the slave is implemented mechanically[6]. With the development of electronics engineering technology, the electronic interface between the two systems becomes possible, which brings the small size of master arms into existence[4]. That is, the shape of the master controller is shifting from the similar shape of the slave robot to the shape of levers or toggle switches which are easy to manipulate for the remote operator[5]. In addition, sensor fusion techniques are under development to improve the virtual reality by combining the tactile, visual, and auditory information. Now, the remote control technology which applied to the fixed-base manipulator is even going to be applied to mobile robots.

In this paper, a virtual reality system is implemented through the visual display and force feedback which is transferred to the operator through the two degrees of freedom force-reflective joystick for a remote operator. In normal operations, the operator watches the working states through the monitor which displays the robot working environment with the aids of a CCD camera. When the robot confronts with an unexpected scenario, the robot may stop or hesitate for a while until it gets a solution from the supervisoring operator. In assembly operations, the visual information is not enough for the operator to resolve the unexpected event. A peg-in-hole operation is a typical task which requires force feedback.

II. System Configuration

In this section, the configuration of a remote operator system is described. To measure the force/torque at the end-effector, a wrist force/torque sensor is used. To capture the information on the robot and working environment, a

CCD camera is installed at the working table, which is sent to the remote operator and displayed on a CRT monitor. To make the operator feel the same force/torque measured at the wrist of the robot and to generate and send the operator's commands to the robot, a two degrees of freedom force-reflective joystick is implemented.

2.1 F/T Sensor

To measure the force/torque at the end-effector, a F/T sensor is attached at the wirst of the robot. This sensor consists of six strain gage bridges and measures 3 components of force and torque respectively. The controller for this sensor is manufactured by Assurance Technology (Model: 30/100), which processes the analog data of six strain gage bridges, transforms to a set of six discrete data, and sends the data to the host controller(PC) through a RS232C serial port. For a set of F/T data, it sends 13 bytes data with the baud rate of 38400bps(bit per second) to PC within 2.8 ms.

2.2 Vision System

To provide the working states and environment of the robot to the remote operator, a CCD camera is attached at (x_c, y_c, z_c) to face to the robot end-effector. The visual information captured by the CCD camera is sent to and displayed at the remote CRT monitor for the operator.

2.3 Joystick System

To recover the force/torque at the end-effector for the operator as well as to generate operator's command, a two degrees of freedom joystick is implemented as shown in Fig. 1. The joystick controller is designed using a 80C196KC micro-processor. This retrieves the force at the joystick base upon the force values F_x and F_y, which are sent from PC for the operator. For this purpose, it drives the two axial motors by sending out PWM(Pulse Width Modulation) output corresponding to the F_x and F_y. To amplify the power, L298N DC motor drives are used.

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

The joystick controller has two main inputs : force data sent from the host controller and position and current data fed back from the joystick.

There exist several constraints in controlling the five degrees of robot using a two degrees of freedom joystick. Among the force/torque components transmitted from the robot, only F_x and F_y are reflected by the joystick. In addition, for the motion commands from the joystick to the robot, four operating modes are set by using two push buttons, which enables the joystick to generate five degrees of freedom motion commands. The mode 0 is used for reflecting the force from the robot at the joystick (neither button is pushed). In this mode, there is no motion command transmission from the joystick to the robot. In mode 1, the up/down variation of the joystick corresponds to the x directional motion commands for the robot; the left/right variation corresponds to the y directional motion commands (bottom button is pushed). In mode 2, the up/down variation of the joystick corresponds to the pitch motion commands for the robot (top button is pushed). In mode 3, the up/down variation of the joystick corresponds to the z directional motion commands for the robot (both buttons are pushed).

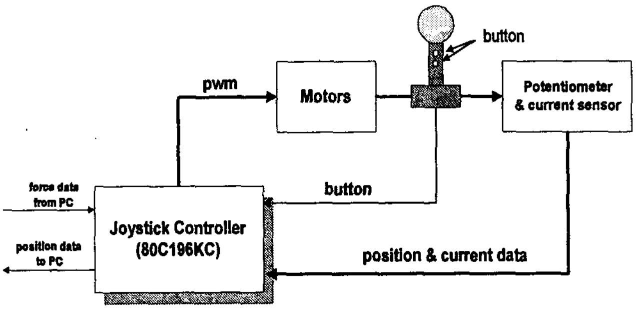

Fig. 1. Block diagram of the joystick system.

2.4 Task Robot System

For our research, a five axis robot (SCORBOT-ER VII) is used, which is shown in Fig. 2. The robot consists of 5 axis: Base (1st axis), Shoulder (2nd axis), Elbow (3rd axis), Pitch (4th axis), and Roll (5th axis). The position coordinates of the robot are represented by the joint angles of 1st, 2nd, 3rd, and 4th axes; the orientational coordinates are represented by the joint angles of 4th and 5th axes. The robot controller which uses a Motorola 68020 as a CPU. The PID algorithm is applied for the position control of electrical DC servo motors and the repetition accuracy is 0.2 mm. The total weight of the robot is 30 Kg and it communicates with the host controller through a RS232C serial port.

2.4.1 Forward Kinematics

Forward kinematics of the task robot are derived as Eqs. (1) ~ (5). In the equations, variables a, b, c, d, and e represent 1st, 2nd, 3rd, 4th, and 5th axis joint angles respectively; variables l_1, l_2, and l_3 represent the link lengths of 2nd axis, 3rd axis, and 4th axis respectively as shown in Fig. 2. The h_1 represents x coordinate of the 2nd link, h_2 is a link offset from the end-effector to the origin along the y-axis, and h_3 is z coordinate of the 2nd link with respect to the robot reference frame. Also x, y, and z represent the cartesian coordinates, and p and r represent the orientation.

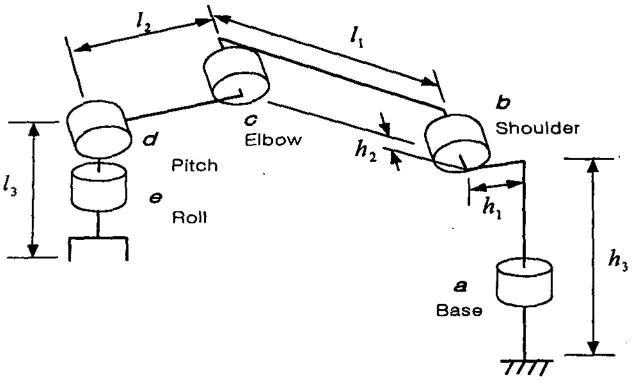

Fig. 2. Structure of SCORBOT-ER Ⅶ Robot.

Forward kinematics for the robot can be represented in terms of three positional coordinates, (x, y, z), and two orientational variables, (p, r), as follows:

$$\begin{aligned} x = {} & (l_1 \times \cos(b) + l_2 \times \cos(b+c) \\ & + l_3 \times \cos(b+c+d) + h_1) \times \cos(a) \\ & - h_2 \times \sin(a) \end{aligned} \tag{1}$$

$$\begin{aligned} y = {} & (l_1 \times \cos(b) + l_2 \times \cos(b+c) \\ & + l_3 \times \cos(b+c+d) + h_1) \times \sin(a) \\ & + h_2 \times \cos(a) \end{aligned} \tag{2}$$

$$\begin{aligned} z = {} & l_1 \times \sin(b) + l_2 \times \sin(b+c) \\ & + l_3 \times \sin(b+c+d) + h_3 \end{aligned} \tag{3}$$

$$p = b + c + d \tag{4}$$

$$r = e \tag{5}$$

In Eq. (4), the pitch, p, in the cartesian coordinates can be obtained as the summation of joint angles of 2nd, 3rd, and 4th axis. Also the roll, r, corresponds to the joint angle of the 5th axis directly as shown in Eq. (5).

2.4.2 Inverse Kinematics

The joint angles of the task robot can be calculated using Eqs. (1) ~ (5), and represented as Eqs. (6) ~ (10).

$$a = \tan^{-1}\frac{y \times Q - x \times h_2}{x \times Q + y \times h_2} \tag{6}$$

$$b = \Phi + \Psi \tag{7}$$

$$c = \tan^{-1}\frac{B - l_1 \times \sin(b)}{A - l_1 \times \cos(b)} - b \tag{8}$$

$$d = p - b - c \tag{9}$$

$$e = r \tag{10}$$

where

$Q = \sqrt{x^2 + y^2 - h_2^2}$, $A = Q - h_1 - l_3 \times \cos(p)$,

$B = z - h_3 - l_3 \times \sin(p)$,

$\rho = \sqrt{L} = \sqrt{A^2 + B^2}$, $\Phi = \tan^{-1}(\frac{B}{A})$,

$\Psi = \cos^{-1}\frac{L + l_1^2 - l_2^2}{2 \times l_1^2 \times \rho}$, and $\Psi > 0$.

Note that $b = \Phi - \Psi$ if b is larger than the maximum allowable angle of the 2nd axis.

2.5 Teleoperated System

For this research, a teleoperated robot system is implemented as Fig. 3 by integrating a F/T sensor, a vision sensor, a joystick system, and a robot system. The functional block diagram of this system is drawn as Fig. 4. The force measured at the robot end-effector is reflected to the force-reflective joystick to enable the operator to feel the contact force. In addition, a CCD camera captures the images of the working environment, which are sent to the CRT monitor for the operator.

In the autonomous mode of the robot, the controller generates commands based upon the pre-programmed algorithm stored in the host controller utilizing the F/T sensor data. The remote operator who feels like he is working at the local task site with the aids of the visual feedback and force reflection generates motion commands for the robot using the joystick. The main mission of the supervisoring operator is to resolve the unexpected situations for the autonomous robot by sending proper commands. At this time, the commands from the operator have the higher priority than the commands generated in the autonomous mode.

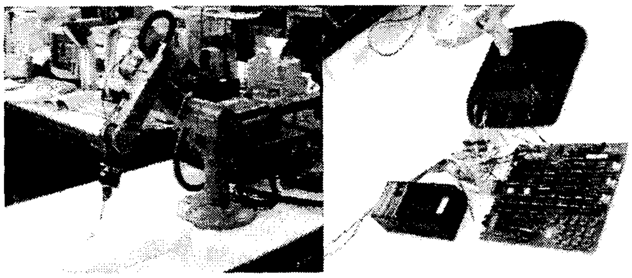

Fig. 3. Teleoperation system.

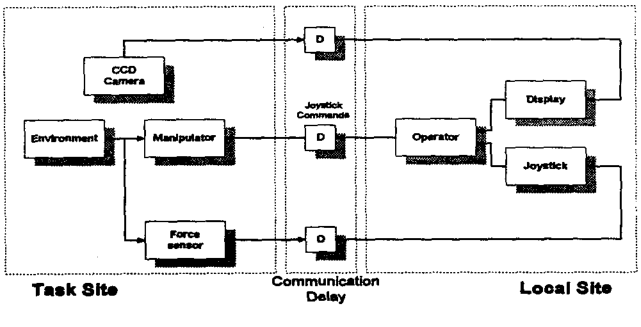

Fig. 4. Block diagram of a teleoperation system.

Ⅲ. Control of a Teleoperation System

The control of teleoperation system is divided into two categories: a remote joystick control and a task robot control. The mission of the joystick is reflecting the F/T values to the operator and is generating the robot position commands for the task robot. The task robot performs the given tasks autonomously based upon the pre-programmed algorithm using the measured force/torque values and the pre-specified position commands. In addition, it also accepts the position commands sent from the operator with the highest priority. In this section, the control systems of remote joystick and the task robot are described.

3.1 Control of Joystick System

The force exerted at the end-effector, F_t, can be measured as the output of the wirst force/torque sensor: F_x, F_y, F_z, T_x, T_y, and T_z. Since two degrees of freedom joystick is used in this research, only F_x and F_y components of F_t are used in reflecting the force at the joystick. F_x represented in the F/T sensor coordinate is transformed into the up/down directional force, J_x, of the joystick while F_y is transformed into the left/right directional force, J_y. The transformations are defined by the Eqs. (11) and (12). Here k_f is a force gain constant. Also the transformation between the position in joystick coordinate and the joint angle of the robot is defined as Eqs. (13) ~ (16). In these equations, Δx is x-axis variation, Δy is y-axis variation, Δz is z-axis variation, and Δp is pitch variation of the robot. Here k_t is a gain constant for transforming the force to positional variations.

$$J_x = k_f \cdot F_x \tag{11}$$

$$J_y = k_f \cdot F_y \tag{12}$$

$$\Delta x = k_t \cdot (J_x \cdot \cos(a) + J_y \cdot \cos(\ a - 90^\circ\ )) \tag{13}$$

$$\Delta y = k_t \cdot (J_x \cdot \sin(a) + J_y \cdot \sin(\ a - 90^\circ\ )) \tag{14}$$

$$\Delta p = k_t \cdot J_x \tag{16}$$

$$\Delta z = k_t \cdot J_x \tag{15}$$

The control block diagram of the joystick is shown in Fig. 5. Here, the force inserted by the operator to the joystick, F_h, is treated as disturbance, which can be estimated by measuring the current flowing through the motor windings. The transfer function from the operator's force, F_h, to the motor current, I_a, is obtained as Eq. (17). It can be rearranged to represent the operator's force; F_h, as Eq. (18).

$$I_a(s) = \frac{E_a(s)}{RJs + BR + KK_b} + \frac{K_b F_h(s)}{RJs + BR + KK_b} \tag{17}$$

$$F_h(s) = \frac{E_a(s)}{K_b} + \frac{(RJs + BR + KK_b) I_a(s)}{K_b} \tag{18}$$

The contact forces, F_x and F_y are sent to the 80C196KC micro-controller and transformed to J_x and J_y for the joystick control. J_x governs the up/down motion of the joystick; J_y governs the left/right motion. Note that the motion or positional variation of the joystick held by the operator generates the reflecting force.

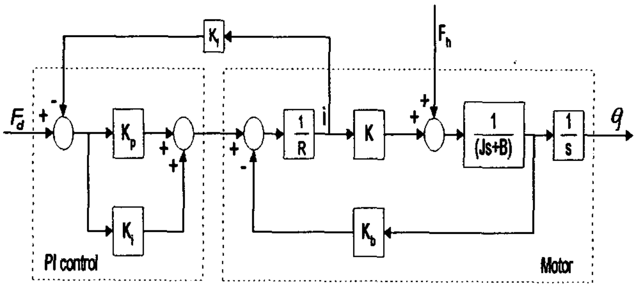

Fig. 5. Block diagram of joystick control system.

3.2 Control of Task Robot

The robot performs the peg-in-hole operation according to the pre-programmed commands in the autonomous mode, as shown in Fig. 6. Initially, the operator sets a start point, P_1, a via point, P_2, and the final point, P_3. Then, the robot carries the peg with a constant velocity from P_1 to P_2 maintaining a certain tilt angle to reduce the friction on the surface. When the peg arrives at P_2, the robot changes the pitch of the peg until it becomes vertical to the hole. Finally, the peg-in-hole task is performed by moving the peg into P_3. During this task, when the robot confronts with unexpected situations, the remote operator who is monitoring the task through the CRT monitor as well as feeling the contact force through the joystick may resolve the problem by giving a pitch offset and a new robot position commands, (x, y, z). Unless the operator is generating a new command, the robot is operating in the autonomous mode.

The host controller compares the desired position, P_d, and the actual position read by the encoder, P_e, and generates a new desired position for the next command. The conventional PID algorithm is applied for the peg-in-hole operation.

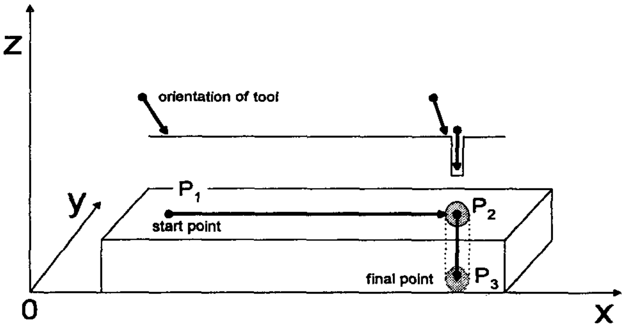

Fig. 6. Experimental environment.

IV. Experiments

The peg-in-hole task is implemented by a robot whose task is monitored by a remote operator, as it is shown in Fig. 6.

4.1 Autonomous Task Execution

The task sequence for the robot is summarized as follows:

① The operator teaches the initial contact point, P_1, the insertion starting point, P_2, and the bottom position of the hole, P_3, to the robot controller.

② The robot moves to the start point, P_1, and then follows a pre-specified path to P_2 with a given velocity.

③ When it arrives at P_2, the robot changes the angle of the peg to be vertical to the hole.

④ The robot moves the peg into the hole along the z axis.

Figs. 7 and 8 represent the x-directional and y-directional forces measured at the end-effector of the robot operating in the autonomous mode. The force values are transmitted to and calibrated by the joystick controller within the bound of $-12.5\,N \sim +12.5\,N$ with offset bias of $7.2\,N$ to make the operator comfortable in feeling the reflected force. As the results of experiment, it is noticed that the reflected force is well following the measured force except during the insertion. During the insertion, the measured force becomes large and fluctuating, since the peg is contacting the hole surface irregularly.

Fig. 9 shows the changes of z and p during the peg-in-hole operation. In the operation, the robot moves along the x axis from a point, P_1, to the point, P_2, until $T = 200\,\text{sec}$, changes it's pitch until $T = 560\,\text{sec}$, and inserts the peg into the hole until $T = 590\,\text{sec}$. Note that at $T = 590\,\text{sec}$, the robot stops the insertion before it reaches to the final point, P_3, since the forces, F_x and F_y, at the end-effector overpasses the driving capability of the robot.

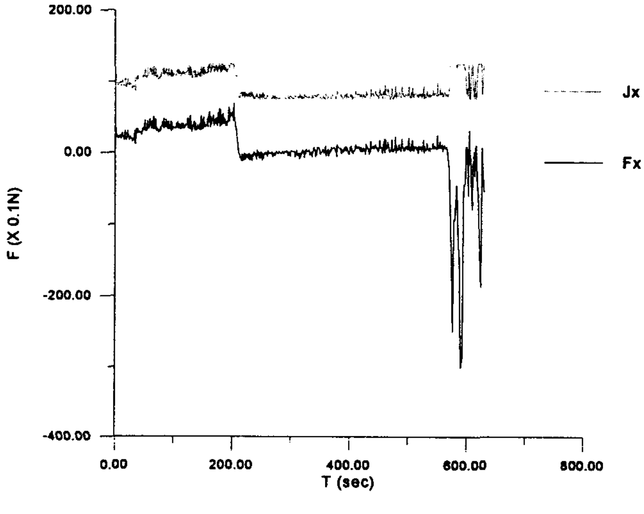

Fig. 7. F_x tracking in the autonomous mode.

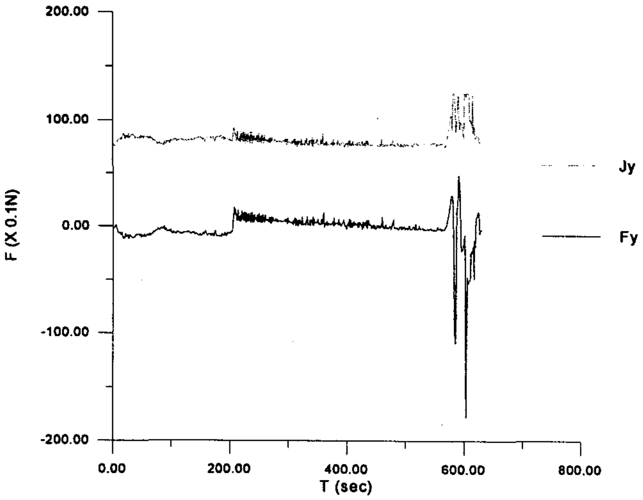

Fig. 8. F_y tracking in the autonomous mode.

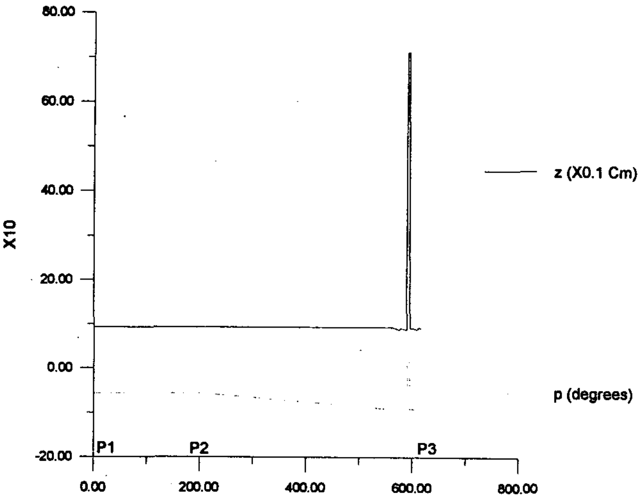

Fig. 9. Position tracking in the autonomous mode.

4.2 Supervisory Task Execution

The robot basically operates in the autonomous mode. However it can not keep the pre-programmed commands when the unexpected events occur. The operator who is grasping the force reflective joystick can perceive the situations by feeling the force at the joystick. At this moment, the operator generates new position commands for the robot using the joystick. This enables the robot to overcome the jamming and continues its work. Unless the operator interrupts the task execution, the robot's operation in the supervisory mode is same as the operation in the autonomous mode. Note that in many cases, the insertion can not he performed without the aids of the operator.

Figs. 10 and 11 show F_x and F_y, and the calibrated forces at the joystick, J_x and J_y. Here, it is noticed that each axial force of joystick follows well to the force of robot end-effector. Fig. 12 shows that the robot keeps its desired trajectory correctly like in the autonomous mode, and it stops at $T = 590\,\text{sec}$. At this moment, the operator adjusts the peg so that the robot moves the peg into the hole until it reaches to P_3 successfully.

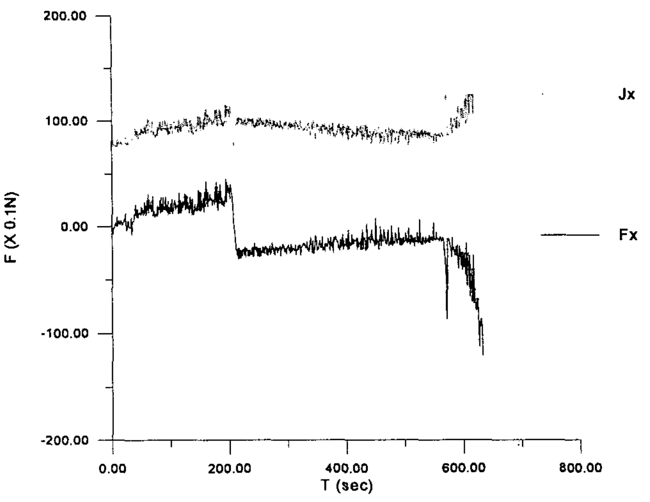

Fig. 10. F_x tracking in the supervisory mode.

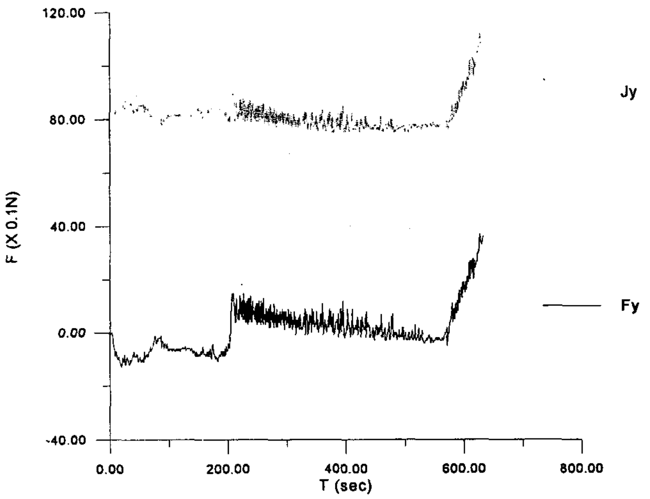

Fig. 11. F_y tracking in the supervisory mode.

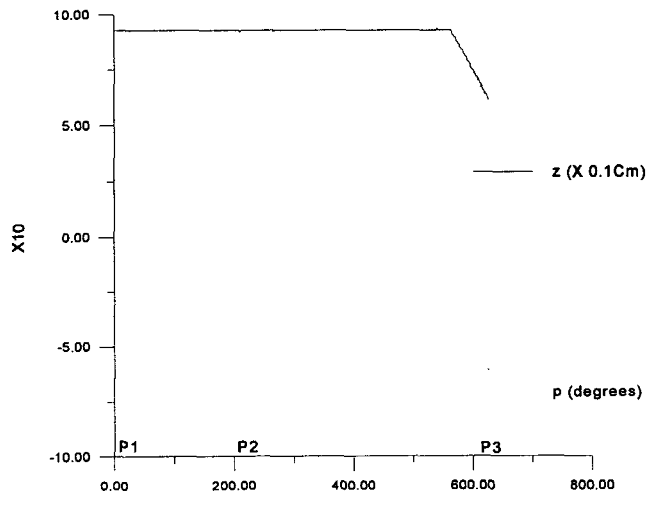

Fig. 12. Position tracking in the supervisory mode.

V. Conclusion

A force reflective joystick system is designed to provide the virtual reality to an operator who is supervisoring a robot's task at the remote site. When the autonomous robot confronts with an unexpected event, it can not handle the problem without the aids of the operator. As a typical example, the peg-in-hole operation is implemented to demonstrate the effectiveness of this force-reflective joystick in resolving the jamming of the peg in the hole, which can not be clearly recognized by only the visual display. For the operator's appropriate decision, a two degrees of freedom force reflective joystick is implemented, which reflects the actual force measured at the wrist of the robot. Through the analysis of the real experiments, the effectiveness of the force reflective joystick is demonstrated. Two problems are left as the future research: 1. Maintaining the constant contacting force during the surface tracking operation, and 2. Overcoming the time-delay which is an inherent barrier in the teleoperation.

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