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Development of Inexpensive Instructional Telemanipulator Test Stations*

N. SEPEHRI
Department of Mechanical and Industrial Engineering, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada

This paper describes the development of inexpensive laboratory setups for demonstrating some aspects of human–computer interaction (HIC) in teleoperated systems. The main objective is to allow undergraduate mechanical and industrial engineering students to design and implement experiments, and to observe issues involved at different stages, from a low-level setpoint control to a high-level task control, within a flexible and adaptive experimental environment. The relatively low-cost test stations described in this paper are currently being used to support the newly developed 'Production and Manufacturing Control Laboratory' as well as a course in robotics and controls. The setups have proved to be very effective in providing complementary practical understanding to students. They may also be used with undergraduate thesis projects.

EDUCATIONAL SUMMARY

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in teaching and demonstration of teleoperated systems to undergraduate mechanical and industrial engineering students, within a flexible and adaptive experimental environment.
2. The paper describes new equipment useful in undergraduate courses/laboratories in 'production and manufacturing control', 'Robotics', and final year 'undergraduate thesis' projects.
3. Third- and fourth-year undergraduates are involved in the use of the equipment. The hydraulic telemanipulator test station may also be used at the graduate level.
4. New aspects of this contribution are: (i) transformation of two donated components into inexpensive flexible instructional, teleoperated test stations; (ii) in-house development of necessary software tools for data acquisition and graphical presentation.
5. The material can be used (as described in the paper) in experiments and/or demonstration which will provide complementary practical understanding to students.
6. The students will be given laboratory instructions for running the setups. The lab manual also includes preliminary background related to the growing field of teleoperation. Other documents, such as the references listed in the paper, are also available to students.
7. The concepts presented have been tested in the classroom, and some results are reported in the paper. The students designed simple experiments and observed some aspects of the human–computer interaction in teleoperated systems. The setups have proved to be very effective; the students understood the concepts faster, since they can see what happens rather than attempt to imagine what should happen.
8. The benefits of this work for engineering education involve relatively low-cost test-stations, which provide unique training tools for undergraduate engineering students to design and test strategies relevant to control and human factors of telemanipulators at a variety of levels. Students can confirm their findings with the explanations provided in the books or other published articles (a 'do-and-see' approach).

INTRODUCTION

THERE exist many engineering applications in which the operator controls a remote manipulator to perform various tasks in hazardous environments. When using remote controls, however, the operator must be familiar with the manipulator configurations and capabilities, including relations between velocities and directions. Sometimes, remote control configurations are not user friendly with respect to the ergonomics and logistics, which may result in undesirable machine reactions due to unintentional errors. This, however, depends upon the application and the degree of involvement of the operator in the control loop, which varies from task planning to direct control of active components [1]. This paper describes the implementation of a project that aims at building test stations to actually observe some of these reactions within a laboratory environment. The project is part of a continuous effort to promote and upgrade the level of engineering education and at the same time to

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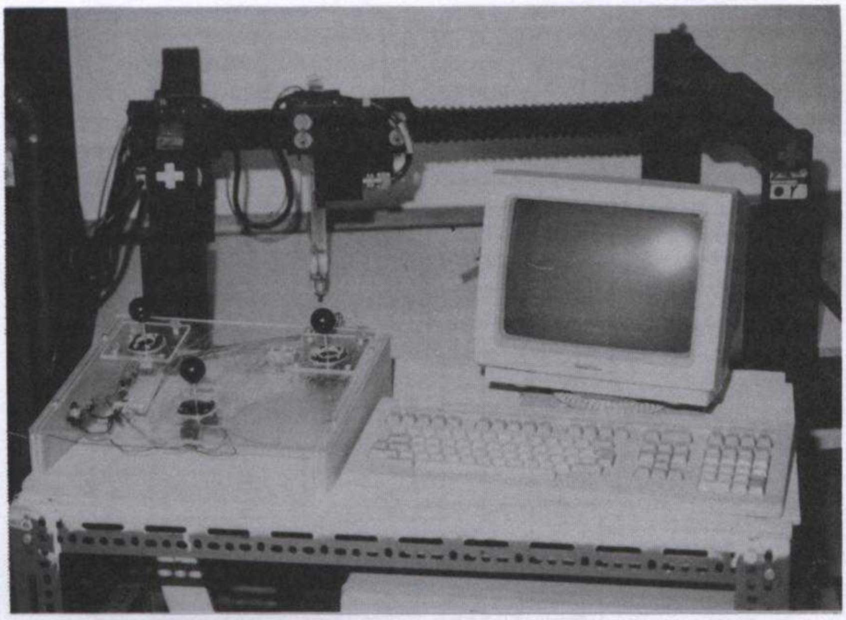

Fig. 1. General view of the *x–y* table.

improve the curriculum to meet the requirement for future engineers.

The emphasis in this project has been placed on developing inexpensive test stations for conducting a variety of simple experiments related to the rapidly changing and growing field of teleoperation. For example, one interesting issue is the concept of co-ordination. By creating an appropriate human–mechanical interface system that can coordinate controls, a decreased demand is placed on the human operator, who can now project his/her thoughts quickly and more efficiently to the controls. The experimental setups described in this paper provide an opportunity for the students to design and perform experiments relevant to this important concept and confirm their findings with the explanations provided in the books [2–5] or other published articles (a 'do-and-see' approach). As a result, the time to understand the concepts will be reduced, since the students can see what happens rather than attempt to imagine what should happen.

The organization of this paper is as follows. First the descriptions of the laboratory test stations which include hardware design and software tools are detailed. Then typical laboratory exercises that have been performed by the students are outlined. Finally, some discussion on future possible experiments with these test stations is presented.

DEVELOPMENT OF TEST STATIONS

Hardware design

Transformation of an *x–y* table.

The *x–y* table shown in Fig. 1 was originally designed for inspecting circuit boards by automatically positioning a video camera, through specialized hardware. The machine was received as a gift, and at that time it was not functional. The mechanical structure of the device plus part of its functional electronics were then utilized to retrofit it as a system having its two axes controlled by joysticks.

Referring to Fig. 2, the movement of the implement in either direction is done by stepper motors. Communication with each stepper motor is in the form of (1) a pulse train—the frequency of which is translated to motor speed, and (2) a digital bit, high or low, to indicate the direction. The pulse train is generated by a voltage-to-frequency converter. Input voltage to the converter is derived from a channel of a digital-to-analog (D/A) board. The command input to the D/A board is digital and is logically derived from an IBM-XT computer [6].

The *x–y* table can now operate with either a pair of spring-centered one-degree-of-freedom joysticks or one two-degree-of-freedom joystick. The joysticks produce analog voltages ± 5 V in proportion to the deflection of each axis from the neutral position. These voltages are read by an analog-to-digital (A/D) board. Depending on the sign and the absolute value of each incoming voltage, a sign bit 0/1 is applied through a D/A board channel, directly to the corresponding stepper motor controller to choose the direction, and an output voltage is applied to the voltage-to-frequency converter. The joystick translations actually control the motor speeds.

Transformation of a Unimate hydraulic robot.

In 1991 the department received, as a gift, a Unimate MK-II hydraulic robot. The robot, which is shown in Fig. 3, was built in 1972. When

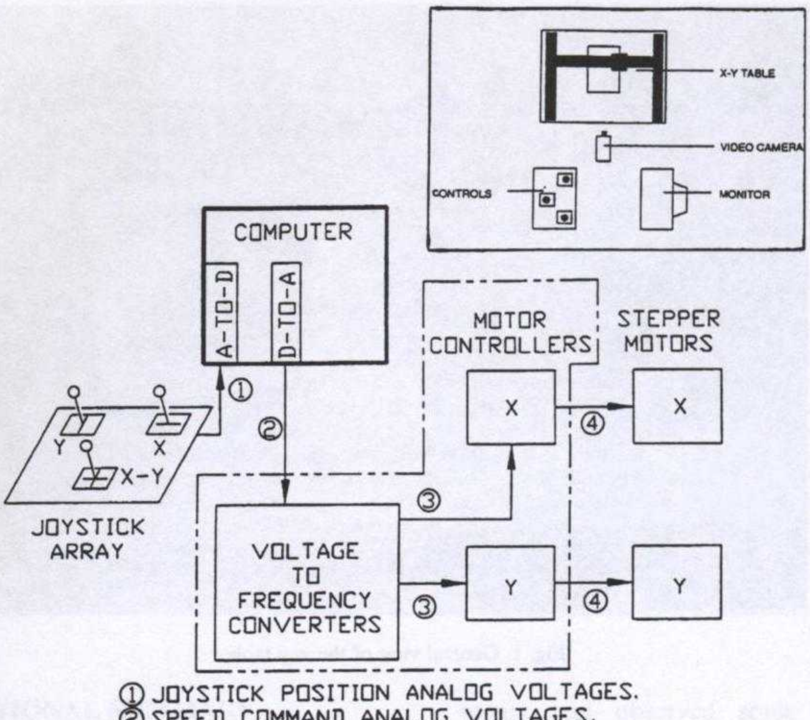

Fig. 2. Schematic representation of the x–y table.

Fig. 3. General view of joystick-controlled hydraulic manipulator.

received, all the original control hardware, which was not functional, was removed with the intention of establishing a research platform for testing different hydraulic function control algorithms. The task of applying data acquisition and interfacing techniques to this rather old but mechanically sound manipulator is summarized here.

The robot had servovalves to control the fluid flows, and encoders to indicate joint angles. By combining these devices and a computer for decision-making, a closed-loop control system was established. The manner in which the computer has been integrated into the system can be best described with reference to Fig. 4. Two three-

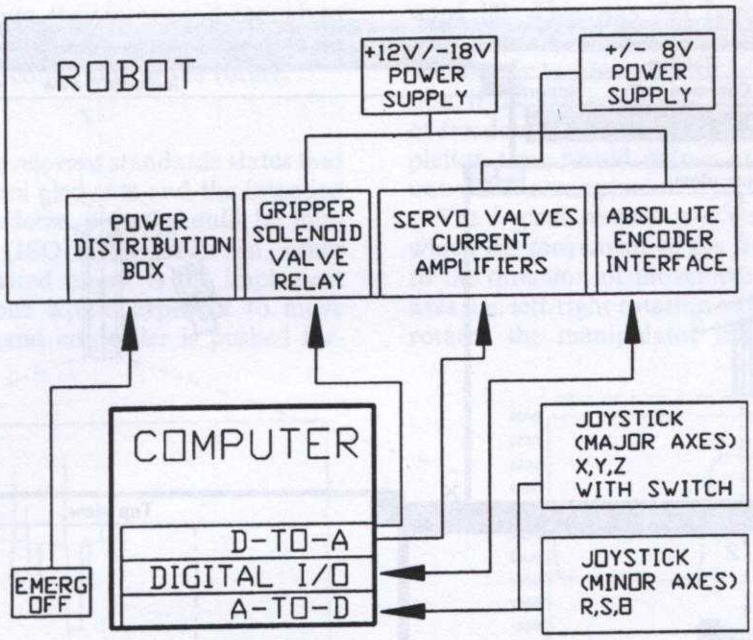

Fig. 4. Hardware configuration of sensory and control system.

degree-of-freedom joysticks are used to control the five axes of the manipulator. Joystick 1 (see Fig. 3) with left/right, up/down and forward/backward motions is used to control rotate-left/right (link 1), up/down (link 2) and in/out (link 3) movements of the manipulator, respectively. The smaller joystick (joystick 2 in Fig. 3) is mounted on a vertical bracket with the stick in a horizontal plane. Up/down motion of this joystick controls the pitch, while rotation about the shaft controls the roll of the gripper. The voltage outputs from both joysticks are read by an A/D card. The computer program reads these analog inputs and, depending on the strategy chosen, outputs analog base voltages to the servovalve current amplifiers. The D/A card allows the computer to output a valve current proportional voltage (± 5 V to produce ± 600 mA current). The valves have closed-center spools with approximately 6% deadbands; they regulate the flows to and from the actuators in proportion to the input currents.

The encoders generate digital-like grey code signals. The grey code translation to binary requires a cascade of exclusive OR (XOR) operation at the bit level. A circuit board has been devised for this operation to reduce the computational time overhead. The digital data from the encoders to the computer are multiplexed. The interface board first selects the encoder signals (one at a time), translates them digitally into binary and presents them to a digital I/O card. Referring to Fig. 4, the arrow pointing to the absolute encoder interface indicates digital input for encoder selection while the arrow pointing to the digital I/O card indicates digital output from this card to the computer. The gripper's solenoid valve is controlled by a digital signal from the D/A card. The ± 12 V power supply is an unregulated source for the servovalve current amplifier. The regulated $+12/18$ V power supply is used for both the encoder interface board and the gripper solenoid.

Software tools

The *x–y* test station allows the operator to simulate tasks such as pushing a log through a gate, pick and place, or tracking. A program has been written which allows the operator to choose using either two single-axis joysticks or the two-dimensional joystick. By executing the program, the operator will be cued to press a key to begin. Once the motor units are switched on, the program collects data and store them in different files. The data are the joystick command trajectories versus time. These trajectories can be graphically viewed on screen or printed.

Similarly, a program has been written for on-line monitoring, displaying and archiving of data acquired from a number of sensors in the hydraulic manipulator. Time in msec, joystick commands in volts, joint angles in degrees, hydraulic line pressures in p.s.i.g. and control input currents to the servovalves in mA are recorded. The joint angular velocities can be calculated using a linear curve-fitting predictive technique. Furthermore, a C++ program has been written to run a window application in which the manipulator is displayed on the computer screen. The program initially uses the Denavit–Hartenberg co-ordinates assigned to different links [7], along with the kinematics parameters. Knowing the current joint angles, the actual configuration of the robot is graphically constructed. Simple wireframe views are drawn on separate windows; *x–y* plane, *x–z* plane, *y–z*

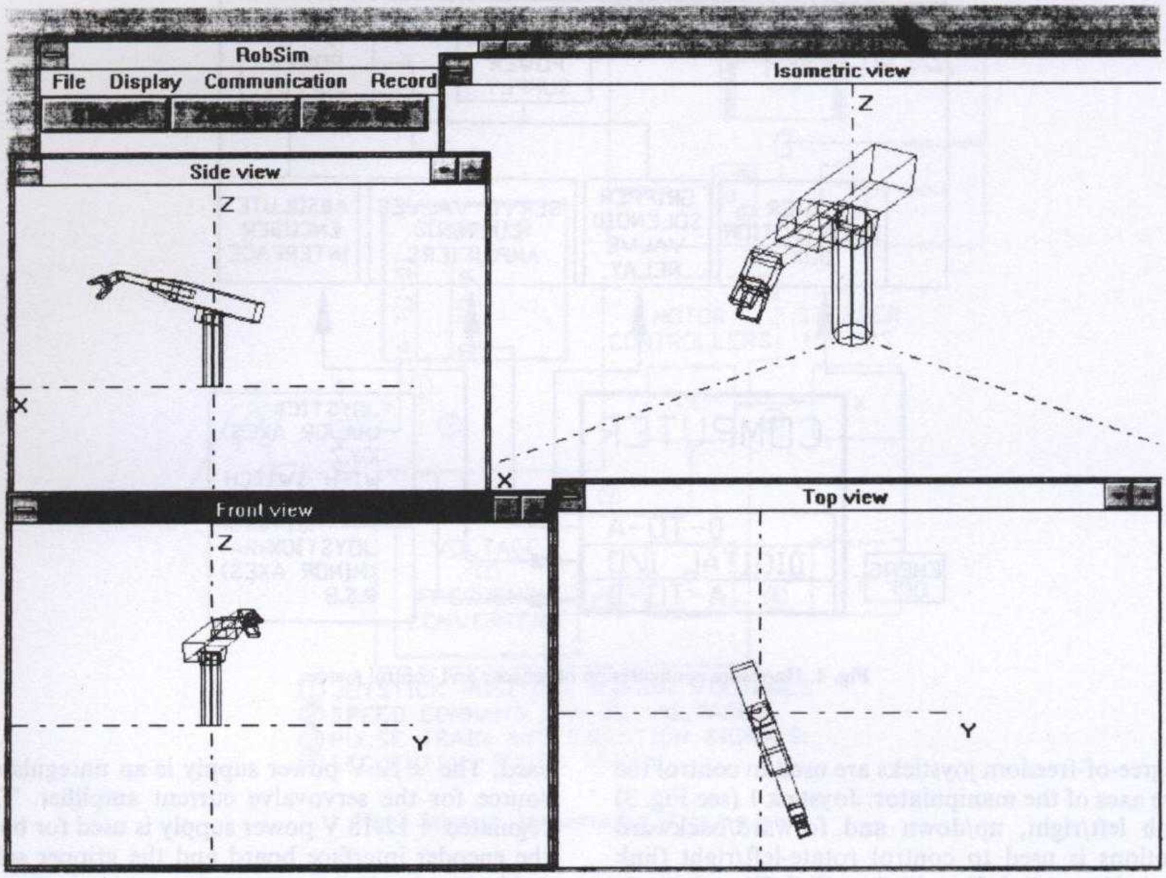

Fig. 5. Example PC display of the hydraulic manipulator.

plane and an isometric view to the three planes (see Fig. 5). These views can be repositioned or enlarged on the screen. When manipulating the robot, the program constantly reads the joint angles through the encoders and update the display in real time.

SAMPLE EXPERIMENTS

In this section typical laboratory experiments that were performed by students are presented. Note that the experiments were all carried out in a velocity control mode in which the deflection of each joystick about one of its axes away from the neutral position resulted in an increase in the velocity of the controlled implement. Also, the dynamics of the mechanical components of the test stations (such as delay and response behavior) were ignored, and only the kinematics aspect of teleoperation was considered. Finally, the test population in these experiments was small and the results were not treated to yield statistically

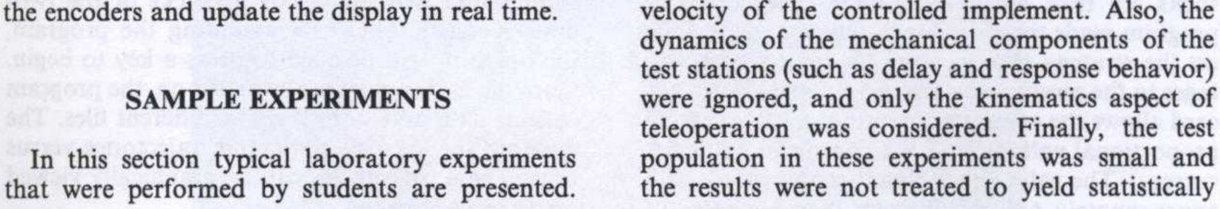

Fig. 6. Typical completion time performance for three operators performing a task under (a) unnatural control pattern, (b) logical control pattern (experiment 1).

accurate data. However, they were good enough to provide insight into the trends which could occur under similar testing conditions in the future.

Experiment 1

One of the existing relevant standards states that 'Movements in control elements and the intended changes in the considered object should be logically coordinated' (ISO 1503-1977). In other words, if the considered object is the implement of a manipulator, one would expect it to move forward when the hand controller is pushed forward [8]. This was the basis of an experiment performed by a group of students. The objective was simply to observe that, in a remote manipulation, if the axis controlled by each joystick degree-of-freedom follows some logical pattern, the completion time would reduce as compared with the unnatural arrangement.

The logical pattern was defined as the one in which the movement of the joystick corresponded to the direction of movement of the manipulator axes, i.e. left/right rotation of the joystick 1 (Fig. 3) rotated the manipulator left or right; up/down

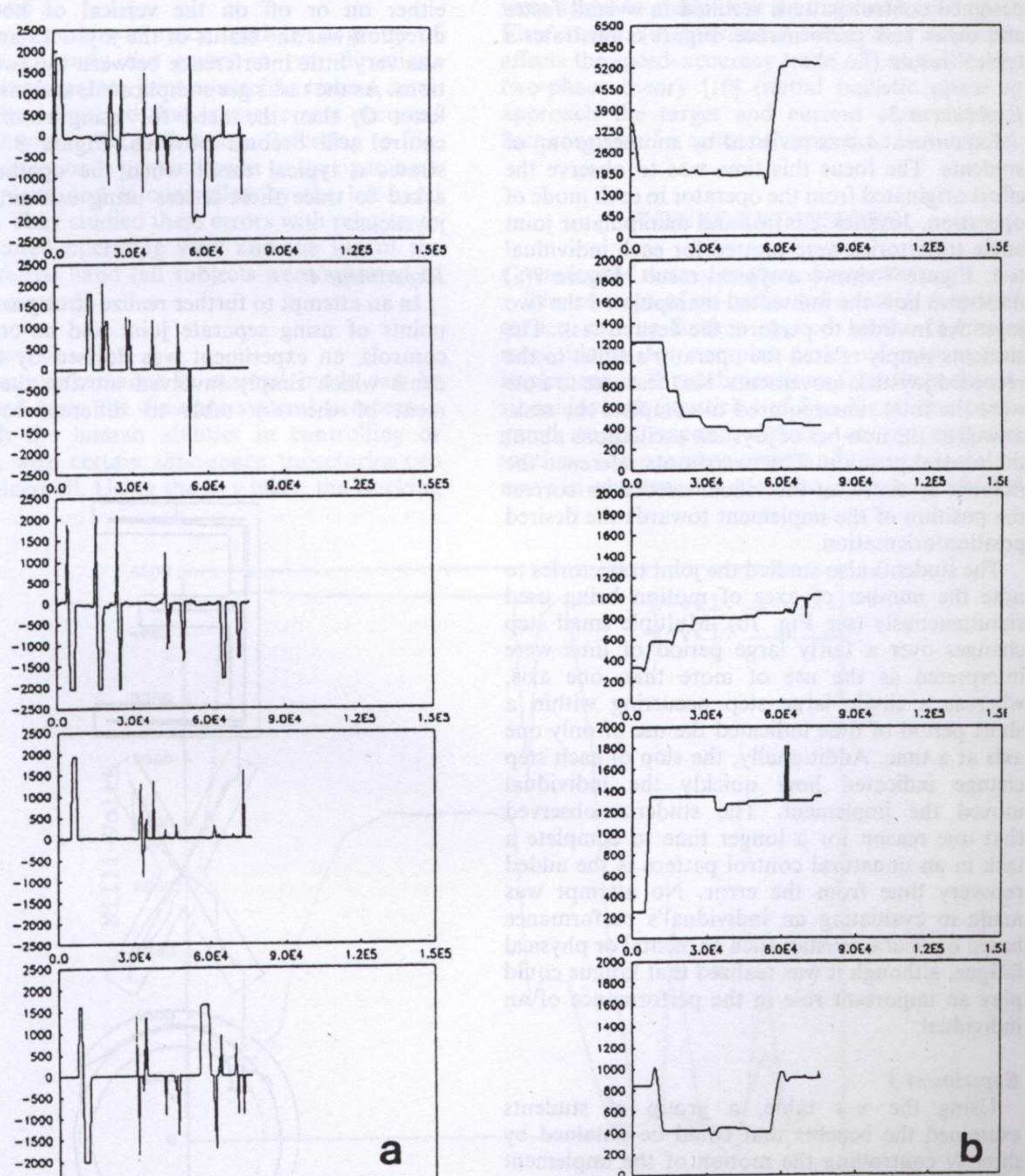

Fig. 7. Illustration of recorded data in a typical pick and place experiment: (a) joystick coordinates; (b) manipulator joint angles (experiment 2).

movement of the joystick allowed the up/down motion of the manipulator; and forward/backward motion of the joystick activated the extend/retract motion of the arm. The unnatural pattern was arranged to be a case in which the control of the latter two joystick actions were reversed.

The students were asked to have different subjects tested over different trials of a pick and placing task. The students observed that the improvement between the experimental runs for the unnatural control pattern was larger and the completion time decreased with the increased operator's experience. However, the intuitively designed control pattern resulted in overall faster and easier task performance. Figure 6 illustrates a typical result.

Experiment 2

Experiment 1 was revisited by another group of students. The focus this time was to observe the effort originated from the operator in each mode of operation. Joystick control and manipulator joint angle trajectories were plotted for each individual test. Figure 7 shows a typical result. Figure 7(a) illustrates how the individual manipulated the two joysticks in order to perform the desired task. The students simply related the operator's effort to the recorded joystick movements. Key features to note were the total time required to complete the task, as well as the number of joystick oscillations about the neutral position. The overshoots reference the number of times an individual needed to correct the position of the implement towards the desired position/orientation.

The students also studied the joint trajectories to note the number of axes of motion being used simultaneously (see Fig. 7b). Multiple small step changes over a fairly large period of time were interpreted as the use of more than one axis, whereas a single large step occurring within a short period of time indicated the use of only one axis at a time. Additionally, the slop of each step change indicated how quickly the individual moved the implement. The students observed that one reason for a longer time to complete a task in an unnatural control pattern is the added recovery time from the error. No attempt was made in evaluating an individual's performance based on characteristics such as mental or physical fatigue, although it was realized that fatigue could play an important role in the performance of an individual.

Experiment 3

Using the x–y table, a group of students examined the benefits that could be obtained by directly controlling the motion of the implement rather than having to co-ordinate the movement of each degree-of-freedom, in order to provide a desired implement motion. This concept, which is referred to as coordinated control, follows the intuitive nature of the human operator, since it combines more than one axis in the controller in an attempt to come closer to a relational environment.

With this background, a group of students designed an experiment which involved tracing the letters E, X and O with a pen while keeping it within a defined boundary. The objective was to show that coordination is desirable if the task requires such coordination. For example the task of tracing letter E implies the activation of one axis at a time; thus, separate joint control would be adequate. In fact, in the case of the x–y table, separate joint control worked better for the letter E, since, it actually resembled a binary situation—either on or off on the vertical or horizontal direction was the status of the joysticks and there was very little interference between the two directions. As the tasks get complicated, such as tracing letter O, then the need for using co-ordinated control will become obvious. Figure 8 demonstrates a typical result when the operator was asked to trace these letters using two single-axis joysticks.

Experiment 4

In an attempt to further realize strong and weak points of using separate joint and co-ordinated controls, an experiment was devised by the students which simply involved moving the implement of the x–y table to different locations,

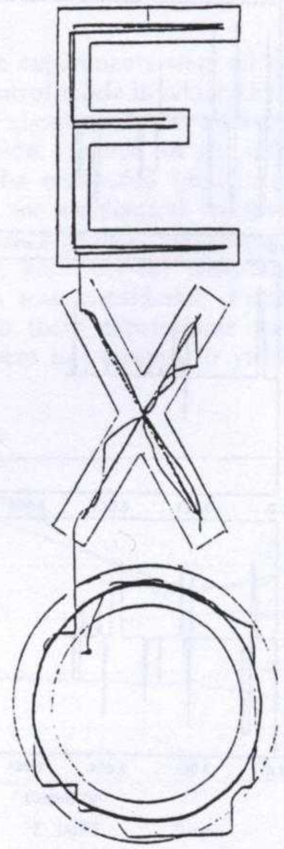

Fig. 8. Typical tracing experiment using separate joint control (experiment 3).

regardless of the path traveled. The students then discussed the difference between the two control modes, in terms of the completion time and the command inputs originated from the joysticks. They further repeated the experiment, this time by viewing a video image of the *x–y* table with the camera located to give a right side view. This was similar to the case when one uses an unnatural correlation between joystick deflections and the corresponding endpoint movements. There was a dramatic time increase to complete the task in both control modes.

Experiment 5

The *x–y* table was once used by a group of students to study the errors in two directions when using separate joint control to trace a curve maze. They observed that largest errors occurred as overshoots in the *y*-direction. Referring to Fig. 2, the *y*-direction is perpendicular to the operator's frontal plane and is controlled by the left-hand joystick. They studied these errors with relation to the obscured operating view and the use of the non-preferred hand (all subjects were reported to be right-handed).

Experiment 6

Human performance in manual mode can be considered from the dynamic systems perspective in which the human abilities in controlling or tracking with certain time-space trajectories can be examined [5]. Using the *x–y* table, the tracking performance can be easily studied by varying the movement amplitudes and the target area sizes. The objective is actually to experience simple statements such as 'faster movements terminate less accurately in a target', and 'targets of smaller areas are reached with slower movements'.

With this background, an experiment was designed which involved using different target sizes at different distances. The two-dimensional joystick movement trajectories (indication of speed) were recorded when the operator moved the implement towards these targets. A typical experimental result is shown in Fig. 9. The students were asked to study their findings with relation to Fitts' studies [9] (movement distance or amplitude affects the speed–accuracy trade-off) as well as the two-phase theory [10] (initial ballistic phase to approach the target and current control phase that consists of a series of correction movements).

FUTURE EXTENSIONS

Co-ordinated control in three dimensions

The concept of co-ordinated control, described earlier, can be further applied to the hydraulic manipulator for complex tasks of moving the implement in three dimensions. The three-dimensional joystick (joystick 1 of Fig. 3) can be reconfigured to correspond directly to the endpoint motion. The operator commands the endpoint to move in whatever direction the joystick is deflected

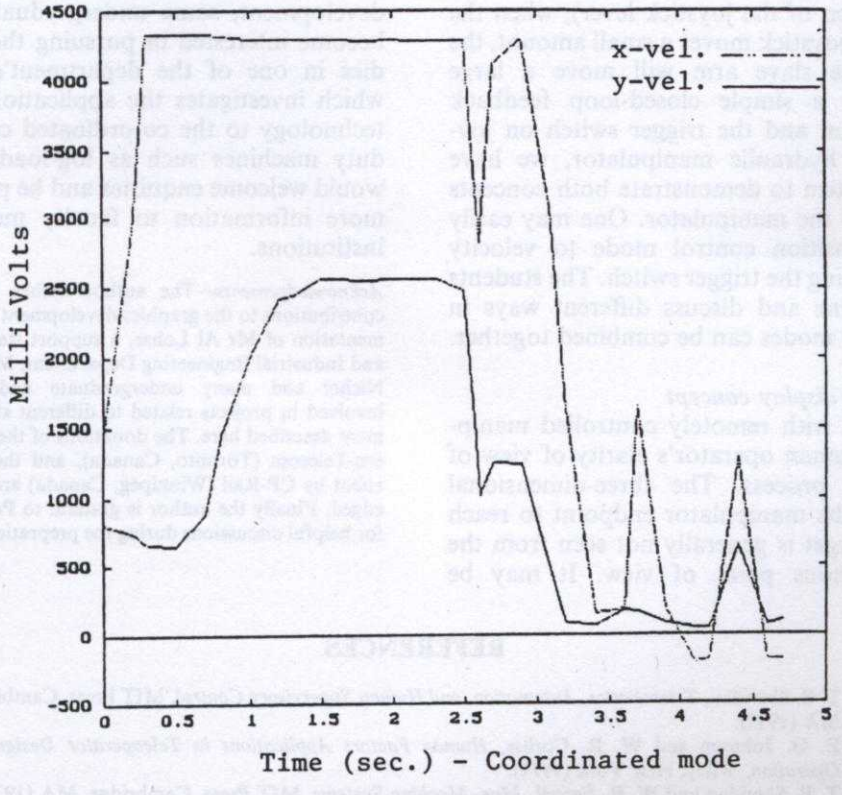

Fig. 9 Typical experimental velocity profiles of Fitt's law movement in *x* and *y* directions during an approach to a target (experiment 6). Target size = 1 cm 6 1 cm, target distance = 30 cm.

from the spring-centered position. Any attempt to reduce the number of directions of the joysticks (e.g. using two single-axis joysticks rather than a two-dimensional joystick on the x–y table) would result with loading the operator with the additional task of having to resolve the intended motion into different components.

The students first study the improvement with this new method, which is inspired by an analogy to human movement. They will then be asked to discover that this improvement requires a computer-based control to translate movements of such a single hand controller into joint commands—the computer should decide on the joint speeds that are required at each moment in time to obtain the desired direction and speed of the implement. The hydraulic manipulator which is now equipped with all software tools allows such an experiment to be performed.

Position control vs. velocity control

As was mentioned earlier, in the previously described experiments, the deflection of a joystick about one of its joint axes away from the neutral position resulted in an increase in the velocity of the controlled joint. This position-to-velocity mapping mode has a certain desirable advantage in that if the hand control is released, all motion stops [8]. On the other hand, the position of the operator's hand controller may map to a position of a manipulator joint. In this position-to-position mapping, if the slave arm (e.g. in/out motion of link 3 of the hydraulic manipulator) is very much larger than that of the master arm (i.e. forward/backward motion of the joystick lever), when the endpoint of the joystick moves a small amount, the endpoint of the slave arm will move a large amount. Using a simple closed-loop feedback control algorithm and the trigger switch on joystick 1 of the hydraulic manipulator, we have developed a system to demonstrate both concepts for any joint of the manipulator. One may easily switch from position control mode to velocity control mode using the trigger switch. The students can then examine and discuss different ways in which these two modes can be combined together.

Computer-aided display concept

One problem with remotely controlled manipulators is the human operator's clarity of view of the 'closing-in' process. The three-dimensional path taken by the manipulator endpoint to reach the intended target is generally not seen from the most advantageous point of view. It may be beneficial to develop a system that would continuously display to the operator the most advantageous view of the closure path between the gripper and the target [1, 11, 12]. In this way the viewpoint is no longer restricted by where the video cameras happen to be. The computer graphics display developed previously can be further enhanced to simulate graphically the manipulator and an object on-screen from different viewing locations. The students will then be able to perform experiments and to understand the promises that can be achieved through computer aiding.

CONCLUDING REMARKS

In this article we have described a project in which some abandoned equipment were transformed into joystick-based human–computer operated test stations. The new facility provided unique training tools for undergraduate engineering students to design and test strategies relevant to control and human factors of telemanipulators at a variety of levels. This flexibility was particularly due to the shift of control, from specialized hardware to software, running on general-purpose computers. The computers are furnished with inexpensive hardware tools and application softwares (all developed in-house). The new setups have also allowed the students (i) to learn and make use of the developed measurement devices and data acquisition tools; and (ii) to test the application of a variety of techniques to the control of hydraulic functions. As a result of this development, some undergraduate students have become interested in pursuing their graduate studies in one of the department's research areas which investigates the application of telerobotics technology to the co-ordinated control of heavy-duty machines such as log-loaders. The author would welcome enquiries and be pleased to furnish more information to faculty members of other institutions.

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Nariman Sepehri is an associate professor in the Department of Mechanical and Industrial Engineering at the University of Manitoba, Canada. He received an M.Sc. (computer-aided process planning) in 1986 and a Ph.D. (telerobotics and control) in 1990—both from the University of British Columbia, Canada. His areas of research interest include automation of heavy-duty industrial (forest and mining) machinery using robotics and advanced control technology. He is a member of ASME and IEEE.