Toward Integrated Operator Interface for Advanced Teleoperation under Time-Ilelay

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Abstract

This paper briefly describes an Advanced Teleoperator (ATOP) system and its control station where a variety of computer-based operator interface devices and techniques are integrated into a functional setting, accomodating a primary operator and secondary operators. Computer graphics is a key operator interface component in the control station where new types of manual interface devices also are employed. The results of some generic and application task experiments are summarized, including the performance of a simulated remote satellite servicing task, carried out under four to eight seconds communication time delay, using satellite TV and Internet computer communication links. In conclusion, the paper highlights the lessons learned so far.

1 Introduction

In general, *teleoperation* implies continuous human operator involvement in the control of remote manipulators. Typically, the human control is a manual one, and the basic information feedback is through visual images. Continuous human operator involvement in teleoperation has both advantages and disadvantages. The disad vant ages become quite dramatic when there is an observable, two-way communication time *delay* between the operator and the remotely controlled equipment. Modern development trends in teleoperators control technology are aimed at amplifying the advantages and alleviating the disadvantages of the human element in teleoperation through the development and use of various non-visual sensors, intelligent or task-level computer controls, computer graphics or virtual *reality* displays, and new computer-based human-machine interface devices and techniques in the information and control channels between the operator and the remotely controlled manipulators. These development trends are typically summarized under the popular titles of **telepresence** and **supervisory control** technologies. In this paper, those two titles are lumped under the term **advanced teleoperation**.

This paper is focused at the description and some practical evaluation of an integrated *operator* interface *system* for advanced teleoperation, developed at the Jet Propulsion Laboratory (J PL), during the past six to seven years, and exercised recently for realistic remote control experiments between JPL in California and the Goddard Space Flight Center'"(GSFC) in Maryland, 4000 Km away from JPL, using satellite TV and computer communication links between JPL and GSFC.

First we describe the J PI, Advanced Teleoperator (ATOP) system and its control station where a variety of operator interface devices and techniques are integrated into a functional setting, accommodating a primary operator and secondary operators. Then, we will summarize the results of some generic and application task experiments. In the third part of the paper, the JPL-GSFC simulated remote satellite servicing task, under communication time delay, will briefly be described. Throughout the paper we will emphasize the design and use of the operator interface elements and their functional integration. In the concluding part of the paper, we will highlight the lessons learned so far.

2 ATOP and its Control Station

The basic underlying idea of the JPL ATOP system setting is to provide a dual arm robot system together with the necessary operator interfaces in order to extend the two-handed manipulation capabilities of a human operator to remote places. The system setting intends to include all perceptive components that are necessary to perform sensitive remote dual-arm manipulation efficiently, including non-repetitive and unexpected tasks. The genera] goal is to elevate teleoperation to a new level of task performance capabilities through enhanced visual and non-visual sensing, computer-aided remote control, and computer-aided human-machine interface devices and techniques. The overall system is divided into two major parts: the remote (robot) work site and the local (control station) site, with electronic data and TV communication between the two sites.

The remote site is a workcell. It comprises: (i) two redundant 8-d. o.f. AAI arms in a fixed base setting, each covering a hemispheric work volume, and each equipped with the latest JPL-developed Model C smart hands which contain 3D force-moment sensors at the hands' base and grasp force sensing at the base of the hand claws, (ii) a J P L-developed cent rol electronics and distributed computing system for the two arms and smart hands, and (iii) a

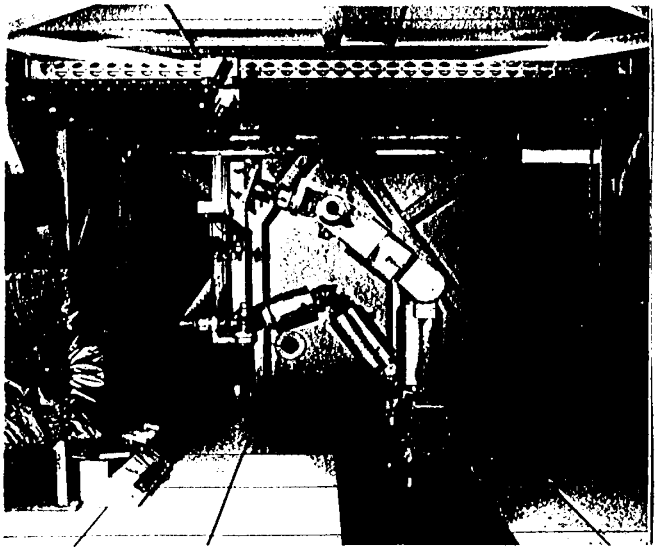

Figure 1: The JPL ATOP Dual Arm Workcell with Gantry TV Frame

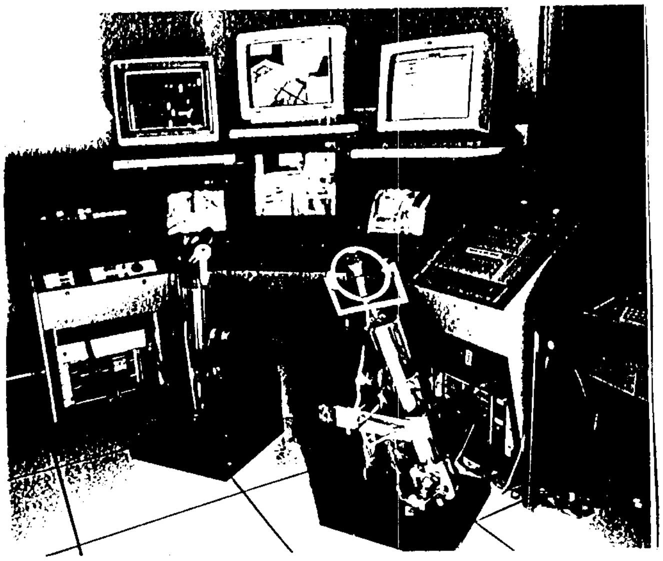

Figure 2: The JPL ATOP Control Station

computer controllable multi-TV gantry robot system with controllable illumination. This gantry robot currently accomodates three color TV cameras, one on the ceiling plane, one on the rear plane, and one on the right side plane. Each camera can be position controlled in two translational d.o.f. in the respective plane, and in two orientation directions (pan and tilt) relative to the respective moving base. Zoom, focus and iris of each TV camera can also be computer controlled. A stereo TV camera system is also available which can be mounted on any of the two side camera bases. The total size of the rectangular remote work site is: about 5 rn width, about 4 m depth, and about 2.5 m bight. See Figure 1 for ATOP remote workcell.

The control station site organization follows the idea of accomodating the human operator in all levels of human-machine interaction, and in all forms of human-machine interfaces. Presently, it comprises: (i) two general purpose Force-Reflecting Hand Controllers (FRHC), (ii) three TV monitor, (iii) a TV camera/monitor switchboard, (iv) manual input device for TV control, and (v) three graphics displays: one is connected to the primary graphics workstation (IRIS 4D/310 VGX) which is used for preview/predictive displays and for various graphical user interfaces (GUI's) in four-quadrant format; the second is connected to an IRIS 4D/70 GT workstation and is solely used for sensor data display; the third one is connected to a SUN workstation (SparcStation 10) and is used as a control configuration editor (CCE), which is an operator interface to the teleoperator control software based on X-window environment. See Figure 2 for ATOP local control station.

2.1 Hand Controllers

The human arm-hand system (thereafter simply called *hand* here) is a key communication medium in teleoperator control, With hand actions, complex position, rate or force commands can be formulated and very physically ***written*** to the controller of a remote robot arm system in all workspace directions. At the same time, the human hand also can receive force, torque, and touch information from the remote robot arm-hand system. Hand controller technology is, therefore, an important technology in the development of advanced teleoperation. The direct and continuous (scaled or unscaled) relation of operator hand motion to the remote robot arm's motion behavior in real time through a hand controller is in sharp contrast to the computer keyboard type commands which, by their very nature, are symbolic, abstract and discrete (non-continuous), and require the specification of some set of parameters within the context of a desired motion.

A new form of bilateral, force reflecting manual control of robot arms has been implemented at the JPL ATOP project. The hand controller is a backdrivable six d.o.f. isotonic joystick. It is dissimilar to the controlled robot arm both kinematically and dynamically. But, through computer transformations, it can control robot arm motion in six task space coordinates (in three position and three orientation coordinates). Forces and moments sensed at the base of the robot hand can back-drive the hand controller through proper computer transformations so that the operator feels the forces and moments acting at the robot hand while he controls the position and orientation of it, This hand controller can read the position and orientation of the hand grip within a 30 crn cube in all orientations, and can apply arbitrary force and moment vectors up to 20 N and 1.0 Nm, respectively, at the hand grip. (This hand controller is visible in Figure 2.)

The computer-based control system supports four modes of manual control: position, rate, force-reflecting, and compliant control In task space (Cartesian space) coordinates. The operator, through an on-screen menu, can designate the control mode for each task space axis independently. Position control mode servos the slave position and orientation to match the master's, The indexing function allows slave excursions larger or smaller than the 30 cm cube hand controller work volume. In force-reflecting mode, the hand controller is back-driven based on force-moment data generated by the robot hand force sensor during the robot hand's interaction with objects and environment. Rate control mode sets slave endpoint velocity in task space based on the displacement of the hand controller. This is implemented through a ***software spring*** in the control computer of the hand controller. Through this software spring, the operator has a sensation of the commanded rate, and the software spring also provides a zero-referenced restoring force. Rate mode is useful for tasks requiring large translations. Compliant control mode is implemented through a low-pass software filter in the hybrid position-force loop. 'l'his permits the operator to control a springy or less stiff robot. Active compliance with damping can be varied by changing the filter parameters in the software menu. Setting the spring parameter to zero in the low pass filter will reduce it to a pure damper which results in a high stiffness hybrid position-force control loop.

The overall control organization permits a spectrum of operations between full manual, ***shared*** manual and automatic, and full automatic (called traded) control, and the control can be operated with variable active compliance referenced to force-moment sensor data. More on the hand controller and on the overall ATOP control system can be found in [I] through [5].

2.2 Computer Graphics

Task visualization is a key problem in teleoperation, since most of the operator's control decisions are based on visual or visually conveyed information. For this reason, computer graphics pays an increasingly important role in advanced teleoperation. This role includes: (i) planning actions, (ii) previewing motions, (iii) predicting motions in real time under communication time delay, (iv) training operators, (v) enabling visual ***perception of non-visible events*** like forces and moments, and (vi) serving as a ***flexible*** operator ***interface*** to the computerized control system.

The actual utility of computer graphics in teleoperation to a higher degree depends on the fidelity of graphics models that represent the teleoperated system, the task and the task environrnent. The JPL ATOP effort in the past few years was focused at the development of high-fidelity calibration of graphics images to actual TV images of task scenes, 'I'his development has four major ingredients. First, creation of high-fidelity 3-D graphics models of robot arms and of objects of interest for robot arm tasks. Second, high-fidelity calibration of the 3-D graphics models relative to given TV camera 2-D image frames which cover the sight of both the robot arm and the objects of interest. Third, high-fidelity overlay of the calibrated graphics models over the actual robot arm and object images in a given TV camera image frame on a monitor screen. Fourth, high-fidelity motion control of robot arm graphics image by using the same cent rol software that drives the real robot.

The high fidelity fused virtual and actual reality image displays became very useful tools for planning, previewing and predicting robot arm motions without commanding and moving the robot hardware. The operator can generate visual effects of robot motion by commanding and controlling the motion of the robot's graphics image superimposed over TV pictures of the live scene. '1'bus, the operator can see the consequences of motion commands in real time, before sending the commands to the remotely located robot. The calibrated virtual reality display system can also provide high-fidelity synthetic or artificial TV camera views to the operator. These synthetic views can make critical" motion events visible that otherwise are hidden from the operator in a given TV camera view or for which no TV camera view is available. More on the graphics system in the ATOP control station can be found in [6] through [9].

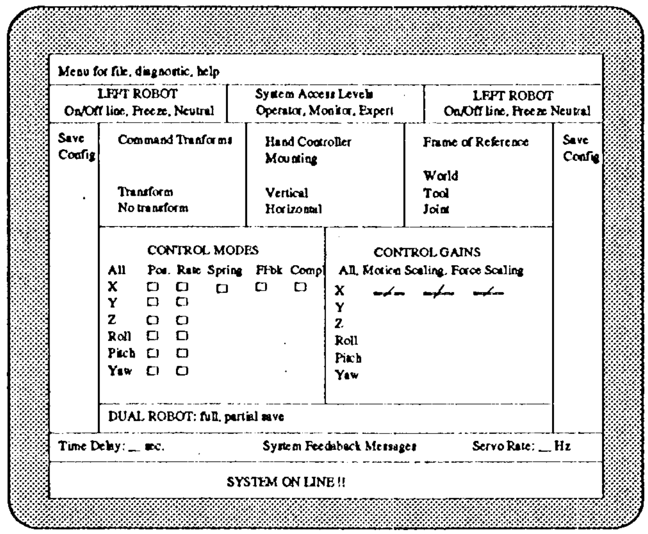

Figure 3: Schematic Layout of the TCE Interface

The first development of a graphic system as an advanced operator interface was aimed at parameter acquisition, and was handled and called as a Teleoperation Configuration Editor (TCE) [10]. This interface used the concepts of Windows, Icons, Menus, and Pointing Device to allow the operator to interact, select and update single parameters as well as groups of parameters (see Figure 3). TCE utilizes the ***direct*** manipulation concept, with the central idea to have visible objects such buttons, sliders, icons, that can be manipulated directly, i.e. moved, and selected using the mouse, to perform any operation. A graphic interface of this type has several advantages over a traditional panel of physical buttons, switches and knobs: the layout can be easily modified and its implementation cycle, i.e. design and validation, is significantly shorter than hardware changes.

The continuing work on a graphic system as an advanced operator interface is aimed at the data presentation structure of the interface problem, and, for that purpose, uses a hierarchical architecture [9]. This hierarchical data interface helps solve the problem of displaying the large amount of data needed for a teleoperation tasks. It looks like a menu tree with only the last menu of the chain (the leaf) displaying data. All the ancestors of the leaf are visible to clearly indicate the nature of the data displayed. The content of the leaf includes data or pictures and quickly conveys the various choices available to the operator. A schematic figure of this layout is shown in Figure 4. Parameters have been organized in four large groups that follow the sequence of steps in a teleoperation protocol. These groups are: (i) Layout, (ii) Configuration, (iii) Tools, (iv) Execution. Each group is further subdivided into specific functions. The *Layout* menu tree contains the parameters defining the physical task structure, such as relative position of the robots and of the FRHC, servo rates etc. The Configuration menu tree contains the parameters necessary to define task phases, such as control mode and control gains. The ***Tools*** tree contains parameters and commands for the off line support to the operator, such as planning, redundancy resolution and software development. Finally, the *Execution* tree contains commands and parameters necessary while teleoperating the manipulators, such as data acquisition, monitoring of robots, hand controllers and smart hands, retrieval of stored configurations and camera commands.

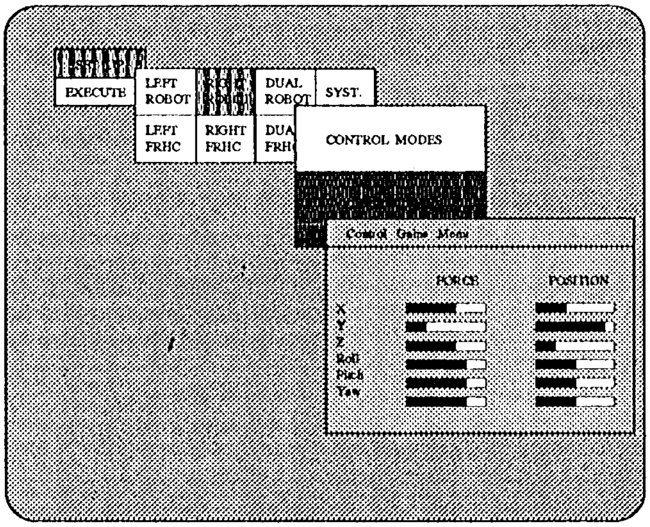

Figure 4: Schematic Layout of the Hierarchical Data Interface

3 Control Experiments

In the generic task experiments, described in detail in [1 1], four tasks were used: attach and detach velcro; peg insertion and extraction; manipulating three electrical connectors; manipulating a bayonet connector. Each task was broken down to subtasks. The test operators were chosen from a population with some technical background but not with an in-depth knowledge of robotics and teleoperation. Each test subject received 2 to 4 hours of training on the control station equipment. The practice of individuals consisted of four to eight 30-minute sessions.

As pointed out in [1 I], performance variation among the nine subjects was surprisingly slight. "Their backgrounds were similar (engineering students or recent graduates) except for one who was a physical education major with training in gymnastics and "co-aching. This subject showed the best overall performance by each of the measures. This apparent correlation between performance and prior background might suggest that potential operators be grouped into classes based on interest and aptitudes.

The generic task experiments were focused at the evaluation of kinesthetic force feedback versus no force feedback, using the specific force feedback implementation techniques of the JPL ATOP project. The evaluation of the experimental data supports the-idea that multiple measures of performance must be used to characterize human performance in sensing and computer aided teleoperation. For instance, in most cases kinesthetic force feedback significantly reduced task completion time. In some specific cases, however, it did not, but it did sharply reduce extraneous forces. More on the results in [1 I].

Application task experiments also were performed, grouped around a simulated satellite repair task. The particular repair task duplicated the *Solar Maximum* Satellite Repair (SMSR) mission, which was performed by two astronauts in Earth orbit in the Space Shuttle Bay in 1984. Thus, it offers a realistic performance reference data base, Our experiment simulated the replacement of the Main Electric *Box* (MEB) of the satellite which comprised the following set of subtasks: thermal blanket removal, hinge attachment for MEB opening, opening of the MEB, removal of electrical connectors, replacement of MEB, securing parts and cables, replug of electrical connectors, closing of MEB, reinstating thermal blanket. It is noted that the two astronauts were trained for this repair on the ground for about a year.

The SMSR repair simulation was organized so that each repair scenario had its own technical justification and performance evaluation objective. For instance, in the first subtask-scenario, performance experiments, alternative control modes, alternative visual settings, operator skills versus training, and evaluation measures themselves were evaluated [12]. The first subtask-scenario performance experiments involved thermal blanket cutting and unscrewing MEB bolts. That is, both subtasks implied the use of tools.

Several important observations were made during the above-mentioned subtask-scenario performance experiments. The two most important ones are: (i) the remote control problem in any teleoperation mode and using any advanced component or technique is at least in 50% a visual perception problem to the operator, influenced greatly by view angle, illumination and contrasts in color or in shading;

(ii) the training or, more specifically, the training cycle has a dramatic effect upon operator performance. It was found that the first cycle should be regarded as a *familiarization* with the system and with the task. For a novice operator, this familiarization cycle should be repeated at least twice. The real training for performance evaluation can only start after completion of a familiarization cycle. The familiarization can be considered as completed when the trainee understands the system 1/0 details, the system response to commands, and the task sequence details. During the second cycle of training, performance measurements should be rnadc so that the operator understands the content of measures against which the performance will be evaluated. Note, that it is necessary to separate each cycle and repetitions within cycles by several days. Once a *personal skill* has been formed by the operator as a consequence of the second training cycle, the real performance evaluation experiments can start. More details on application task experiments can be found in [12].

'I'he practical meaning of training is, in essence, to help the operator develop a ***mental model*** of the system and of the task. During task execution, the operator acts through the aid of this mental model. It is, therefore, critical that the operator understands very well the response characteristics of the sensing and computer-aided ATOP system which has a variety of selectable control modes, adjustable control gains and scale factors.

The procedure of operator training and the expected behaviour of a skilled operator following an activity protocol offers the ***idea of*** providing ***the operator*** with performance ***feedback messages*** on the operator interface graphics, derived from a stored model of the task execution. A key element for such advanced performance feedback tool to the operator is a program that can follow the evolution of a telopcrated task by segmenting the sensory data stream into appropriate phases.

A task segmentation program of this type has been implemented by means of a Neural Network architecture [13] and it is able to identify the segments 'of a peg-in-hole task.

Figure 5 is the output of an experiment of the peg-in-hole task. Three curves are plotted in this figure: the X axis force ***signal*** input to the network, the **real time *output*** of the network (dotted line) and the ***off-line classification*** of the network (solid line). The dotted line shows the actual output of the classifier and the solid line is the the output of the off-line segmentation of the same data. The values of the segments in the two lines are the indices of the peg-in-hole phases, as described in [14]. On the solid line, phase transitions are synchronous with the corresponding data, since the data rate is determined by the processing speed of the network. The dotted line, instead, shows a lag between its phase transitions and the solid line ones, due to the low speed of the on-line segmentation. In the real time segmentation, the delay between corresponding transitions increases a-s a function of the time elapsed from the beginning of the experiment, since samples arrive to the network at a much higher rate than their propagation speed through the network.

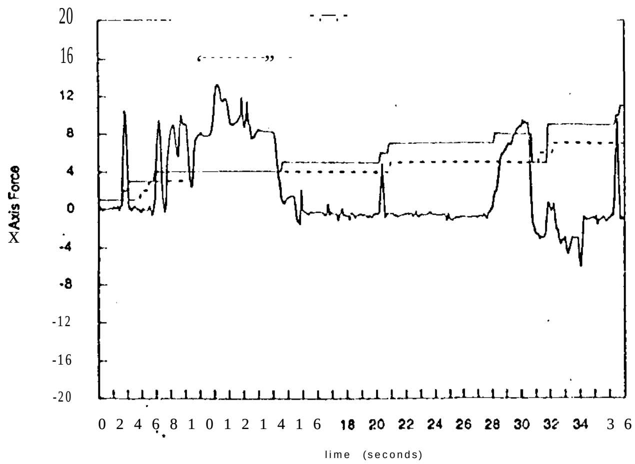

Figure 5: Segmentation in the Real-Time Experiment for a Peg-in-Hole Task

4 A Time-Delay Experiment

The benefits of integrated operator interface to sensing and computer control aided and computer graphics supported advanced teleoperation system become most convincing when the operation" has to be performed under communication time delay. The technical meaning of integrated ***operator*** interface for such cases signifies two major features of the overall ATOP architecture: (i) the operator, through high fidelity overlay of computer graphics images of work scenes (virtual reality) over TV camera images of the same work scenes (actual reality), can, with high visual fidelity, preview and predict the outcome of command and control actions in real time; (ii) the operator can, with high cognitive confidence, ***delegate some commands and control authority to the sensor-based closed loop remote control*** based on visual preverification of the expected action domain of that control loop.

4.1 Calibration Method

A high-fidelity overlay of graphics and TV images of work scenes requires a high fidelity TV camera calibration and object localization relative to the displayed TV camera view. Theoretically, this can be accomplished in several ways. For the purpose of simplicity and operator-controllable reliability, an operator-interactive camera calibration and object localization technique has been developed, using the robot arm itself as a calibration fixture, and a non-linear least-squares algorithm combined with a linear one as a new approach to compute accurate calibration and localization parameters.

The current method uses a point-to-point mapping procedure, and the computation of camera parameters is based on the ideal pinhole model of image formation by the camera. In the camera calibration procedure, the operator first enters the correspondence information between the 3-D graphics model points and the 2-I) camera image points of the robot arm to the computer. This is performed by repeatedly clicking with a mouse a graphics model point and its corresponding TV image point for each corresponding pair of points on a monitor screen which, in a four-quadrant window arrangement, shows both the graphics model and the actual TV camera image. (See Figure 6). '1'0 improve calibration accuracy, several poses of the manipulator within the same TV camera view can be used to enter corresponding graphics model and TV images points to the computer. Then the computer computes the camera calibration parameters. Because of the ideal pinhole model assumption, the computed output is a single linear 4 by 3 calibration matrix for a linear perspective projection. Object localization is performed after camera calibra-

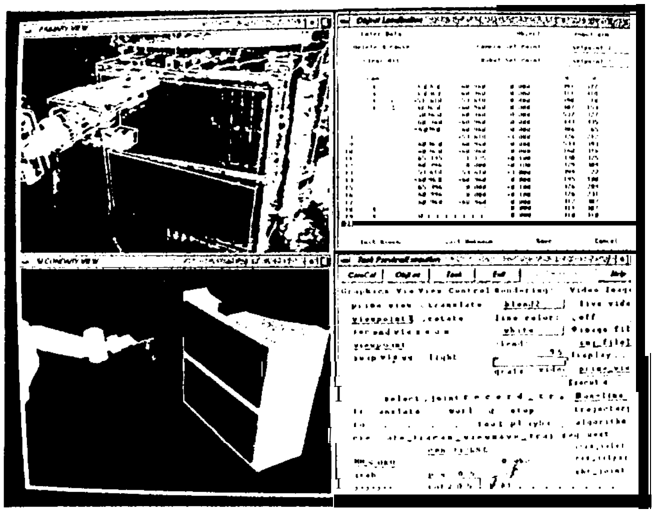

Figure 6: Graphics User Interface for 'Calibrating Virtual (Graphics) Images to TV Images

tion, by entering corresponding object model and TV image points to the computer for different TV camera views of the object. Again, the computational output is a single linear 4 by 3 calibration matrix for a linear perspective projection,

The actual camera calibration and object localization computations are carried out by a combination of linear and non-linear least-squares algorithms. The linear algorithm, in general, does not guarantee the orthonorrnality of the rotation matrix, providing only an approximate solution. The non-linear algorithm provides the least-squares solution that satisfies the orthonormality of the rotation matrix, but requires a good initial guess for a convergent solution without entering into a very time-consuming random search. When a reasonable approximate solution is known, onc can start with the non-linear algorithm directly. When an approximate solution is not known, the linear algorithm can be used to find one, and then one can proceed with the non-linear algorithm. More on the calibration and object localization technique can be found in [15].

After completion of camera calibration and object localization, the graphics models of both robot arm and object of interest can be overlaid with high fidelity on the corresponding actual images of a given TV camera view. The overlays carr be in wire-frame or solid-shaded polygonal rendering with varying levels of transparency, providing different visual effects to the operator for ditrr-rent task details. [n the wire-frame format, the hidden lines can be removed or retained by the operator, dependent on the information needs in a given task.

4.2 Performance Results

The performance capabilities of the high-fidelity graphics overlay preview/predictive display technique were demonstrated on a large laboratory scale in May 1993. A. simulated life-size satellite servicing task was set up at GSFC and controlled 4000 Km away from the JPL ATOP control station. Three fixed camera setting were used at the GSFC worksite, and TV images were sent to the JPI, control station over the NASA-Select Satellite TV channels at video rate. Command and control data from JPL to GSFC and status and sensor data from GSFC to JPI, were sent through the Internet computer communication network. The roundtrip comrnand/inforrn ation time delay varied between four to eight seconds between the GSFC worksite and the J PL control station.

The task involved the exchange of a satellite module. This required inserting a 45 crn long power screwdriver, attached to the robot arm, through a 45 crn long hole to reach the module's latching mechanism at the module's backplane, unlatching the module from the satellite, connecting the module rigidly to the robot arm, and removing the module from the satellite. The placement of a new module back to the satellite's frame followed the reverse sequence of actions.

Four camera views were calibrated for this experiment, entering 15 to 20 correspondence points in total from 3 to 4 arru poses for each view. The calibration and object localization errors at the critical tool insertion task amounted to about 0.2 cm each, well within the allowed insertion error tolerance. This 0.2 cm error is referenced to the zoom-in view (fovy=8°) from the overhead (front view) camera which was about 1 m away from the tool tip. For this zoom-*in* view, the average error on the image plane was typically 1.2 to 1.6 % (3.2 to 3.4 % maximum error); a 1.4 % average error is equivalent to 0.2 cm displacement error on the plane 1 m in front of the camera.

The idea with the high-fidelity graphics overlay image over a real TV image is that the operator can interact with it visually in real time on a monitor within one perceptive frame when generating motion commands manually or by a computer algorithm. Thus, this method compensates in real time for the operator's visual absence from reality due to the time-delayed image, Typically, the geometric dimensions of a monitor and geometric dimensions of the real work scene shown on the monitor are quite different, For instance, an 8-inch long trajectory on a monitor can correspond to a 24-inch long trajectory in the actual work space, that is, three times longer than the apparent trajectory on the monitor screen. Therefore, to preserve fidelity between previewed graphics arm image and actual arm motions, all previewed actions on the monitor were scaled down very closely to the expected real motion rate of the arm hardware. The manually generated trajectories were also previewed before sending the motion commands to the GSFC control system in order to verify that all motion data were properly recorded. Preview displays contribute to operational safety. In order to eliminate the problem associated with the varying time delay in data transfer, the robot motion trajectory command is not executed at the GSFC control system until all the data blocks for the trajectory are received.

An element of fidelity between graphics arm image and actual arm motion was given by the requirement that the motion of the graphics image of the arm on the monitor screen be controlled by the same software that controls the motion of the actual arm hardware. This required to implement the GSFC control software in the JPL graphics computer.

A few seconds after the motion commands were transmitted to GSFC from JPL, the JPL operator could view the motion of the real arm on the same screen where the graphics arm image motion was previewed. If everything went well, the image of the real arm followed the same trajectory on the screen that the previewed graphics arm image motion previously described, and the real arm image motion on the screen stopped at the same position where the graphics arm image motion stopped earlier. After completion of robot arm motion, the graphics images on the screen were updated with the actual final robot joint angle values. This update eliminates accumulation of motion execution errors from the graphics image of robot arm, and retains graphics robot arm position fidelity on the screen even after the completion of a force sensor referenced compliance control action.

The actual contact events (moving the tool within the hole and moving the module out from or in to the satellite's frame) were automatically controlled by au appropriate compliance control algorithm referenced to data from a force-moment sensor at the end of the robot arm.

The experiments have been performed successfully, showing the practical utility of high-fidelity predictive-preview display techniques, combined with sensor-referenced automatic compliance control, for a demanding telerobotic servicing task under communication time delay. More on these experiments and on the related error analysis can be found in [16]. Figure 7 illustrates a few typical overlay views.

A few notes are in place here, regarding the use of calibrated graphics overlays for time-delayed remote control. (i) There is a wealth of computation activities that the op crater has to exercise. This requires very careful design considerations for an easy and user friendly operator interface to this computation activity. (ii) The selection of the matching graphics and TV image points by the operator has an impact on the calibration results. First, the operator has to select significant points. This requires some rule-bsscd knowledge about what is a significant point in a given view. Second, the operator has to usc good ***visual acuity*** to click the selected significant points by the mouse.

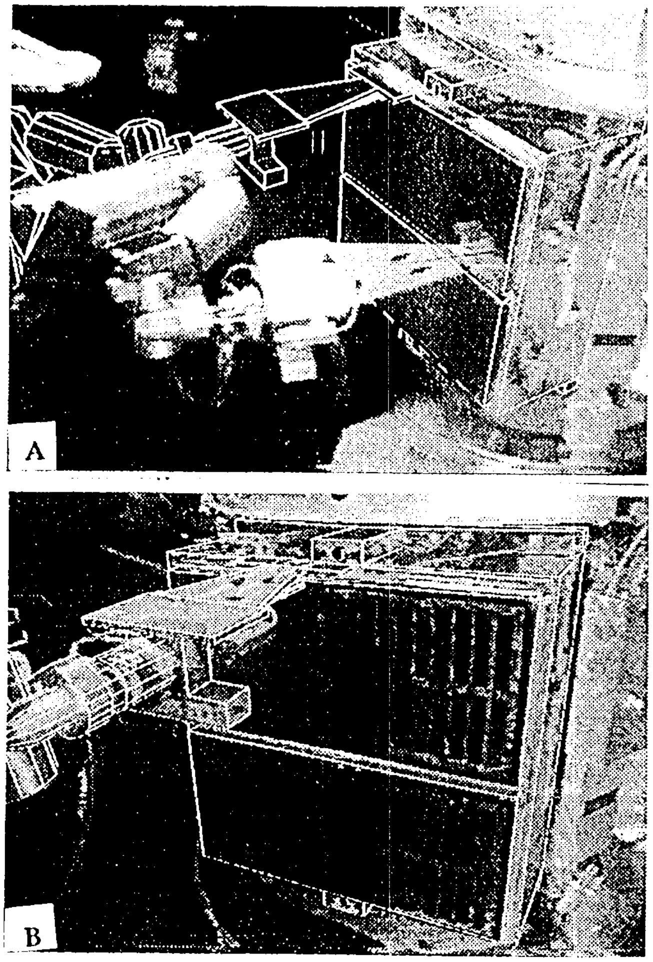

Figure 7: (A) Predictive/Preview Display of End Point Motion. (B) Status of Predicted End Point after Motion Execution, from a Different Camera View, for the Same Motion Shown Above.

5 Conclusions

The following general conclusions emerged so far from the development and experimental evaluation of the JPL ATOP:

1. The sensing, computer and graphics aided advanced teleoperation system truly provides new and improved ***technical features. In*** order to transform these features into new and improved *task performance* capabilities, the operators of the system have to be transformed from naive to ***skilled operators.*** This transformation is primarily an undertaking of educat ion and training.

2. To carry out an actual task requires that the operator follows a clear procedure or protocol which has to be worked out off-line, tested, modified and finalized. It is this procedure or protocol following habit that finally will help develop the experience and skill of an operator.

3. The final skill of an operator can be tested and graded by the ability of successfully improvising to recover from unexpected errors in order to complete a task.

4. The variety of 1/0 activities in the ATOP control station requires workload distribution between two operators. The primary operator controls the sensing and computer aided robot arm system, while the secondary operator controls the TV camera and monitor system and assures protocol following. Thus, the coordinated training of two cooperating operators is essential to successfully usc the ATOP system for performing realistic tasks. It is yet not know what a single operator could do and how. To configure and integrate the current ATOP control station for successful usc by a single operator is a challenging R&D work.

5. The problem of ATOP system development is not so much the improvements of technical components and subsystems. Though, they also present challenges, The final challenge is, however, to integrate the improved *technical features* with the natural capabilities *of* the *operator* through appropriate human-machine interface devices and techniques to produce an improved overall system *performance* capability in which the operator is part of the system in some new way.

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