THE ROLE OF COMPUTER GRAPHICS IN INTELLIGENT REMOTE CONTROL OF UNDERWATER VEHICLE AND MANIPULATOR SYSTEMS

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Abstract

Computer graphics or "virtual reality" techniques can aid task visualization for planning, action previews and predictions, operator training, and visual perception of non-visible events in telerobotic operations. The utility of computer graphics in remote control can be significantly enhanced by high-fidelity calibration of virtual reality images to actual TV camera images. A calibration technique, developed at the Jet Propulsion Laboratory (JPL), is briefly described, and its demonstration is quoted, This calibration technique, with proper modifications and additions, could be extended to underwater visual conditions.

INTRODUCTION

The terms "remote control", "teleoperation" or "telerobotics" denote operations where the robotic system and operator are physically separated by some distance, and there may exist some communication time delay between the operator and remote robot. A key feature of this operation setting is that the operator's perceptive, cognitive, and manual skills are required to perform the remote operation successfully and efficiently in a control station, The purpose of this paper is to describe and discuss computer graphics (or popularly "virtual reality") techniques that can aid the operator to elevate teleoperation to new levels of performance capabilities.

The role of computer graphics displays in teleoperation includes (i) task visualiztion for planning teleoperator actions, (ii) motion or action preview prior to actual execution of motion, (iii) predicting motions m real time when there is a communication time delay between operator control station and remote robot, (iv) help operator training before the operator starts exercising the remote hardware, (v) enable visual perception of non-visible events, and, in general, to serve as a flexible operator interface modality to the remote system [1, 2],

Task visualization is a key problem in teleoperation since most of the operator's control decisions are based on visual information. The capability of previewing motions enhances the quality of teleoperation by reducing trial-and-error approaches in the hardware control and by increasing the operator's confidence in control decision making during task execution. Predicting consequences of motion commands in real time under communication time delay permits longer action segmentations as opposed to the short action segmentations used in the move-and-wait control strategy when no predictive display is available, increases operation safety, and reduces total operation time. Operator training through a display system is a convenient tool for initial familiarization of the operator with the teleoperated system without actually turning the hardware system on. Visualization of non-visible events enables a graphical representation of different non-visual sensor data and helps management of system redundancy by providing a suitable geometric picture of a multi-dimensional system state.

CALIBRATED VIRTUAL REALITY

The actual utility of computer graphics in teleoperation to a high degree depends on the fidelity by which the graphic models represent the teleoperator system, the task, and task environment. The JPL advanced teleoperation effort in the past few years was focused on the development of high-fidelity calibration of graphics displays. This development has four major ingredients: First, creation of high-fidelity 3-D graphics models of remotely operated 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 overlaying of the calibrated graphics models over the actual robot arm and object images in a given TV camera image frame on a monitor screen as seen by the operator. Fourth, high-fidelity motion control of robot arm graphics image by using the same control software that drives the real robot.

These high-fidelity fused virtual and actual reality displays became very useful tools for planning, predicting, and previewing robotic actions, without commanding and moving the actual robot hardware. The operator can generate visual effects of robotic motion by commanding the motion of the graphics image of the robot superimposed over TV pictures of the live scene. Thus, the operator can see the consequences of motion commands in real time, before sending the commands to the remotely located robot. This calibrated virtual reality display system can also provide high-fidelity synthetic or artificial TV camera views to the operator. These synthetic views make critical robot 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.

FUSED VIRTUAL AND ACTUAL IMAGES

Fusion of graphics and actual TV images can be generated by overlaying graphics images over actual TV images. A high-fidelity overlay requires a high-fidelity TV camera calibration and object localization. For this purpose, a reliable operator-interactive camera calibration and object localization technique has been developed. The current calibration uses a point-to-point mapping procedure, and the computation of the camera calibration parameters is based on the ideal pinhole model of image formation by the camera. First, the camera calibration is performed by using the manipulator itself as a calibration fixture. The operator enters the correspondence information between 3-D graphics mode] points and 2-D camera image points of the manipulator 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 on a monitor screen which shows both the graphics model and the actual TV camera images. To improve calibration accuracy, several poses of the manipulator within the same TV camera view can be used to enter corresponding model and TV image 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 4X3 calibration matrix for a linear perspective projection. This matrix describes the relation between 3-D object points and their corresponding 2-D image points in homogeneous coordinates.

Object localization is performed after camera calibration, entering cm-responding object model and TV image points to the computer for different desired TV camera views. Again, the output is a single linear 4X3 calibration matrix for a linear perspective projection.

The actual camera calibration and object localization computations are carried out by a combination of linear and nonlinear least-squares algorithms, and the computational procedure depends upon whether an approximate initial solution is known.

After completing camera calibration and object localization, the graphics models of both the robot arm and the object can be overlaid with high fidelity on the corresponding actual images in a given TV camera view. The overlays can be in a wire-frame or solid-shaded polygonal rendering with varying levels of transparency, providing different visual effects to the operator for different task details. In a wire-frame format, the hidden lines can be removed or retained by the operator, dependent on the information needs in a given task. The camera calibration and graphics-video overlay procedures are schematically summarized in Figures 1 and 2.

More on the calibration and overlay techniques can be found in [3, 4], including experimental results. The implementation today employs a Silicon

Graphics IRIS 4D/310 VGX workstation with a square pixel resolution monitor and with a VideoLab Board for video image capture and for calibrated graphics overlay on the live video image. Software is in 'C running under UNIX.

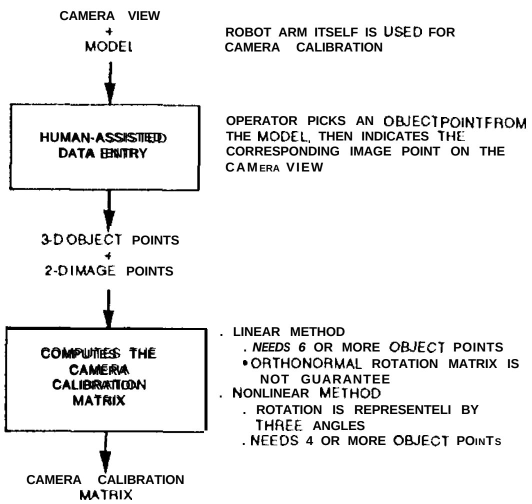

Fig 1, Camera calibration procedure schematic

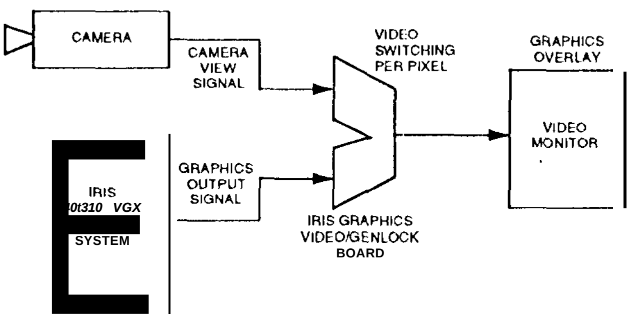

Fig 2. Graphics-video overlay procedure schematic

DEMONSTRATION AND COMMERCIALIZATION

The performance capabilities of the high-fidelity graphics overlay preview/predictive display technique described above was demonstrated on a large laboratory scale in May, 1993. A simulated life-size satellite servicing task was set up at the Goddard Space Flight Center (GSFC) in Maryland, and controlled 2500 miles away from the JPL control station. Three fixed TV camera settings were used at the GSFC worksite, and TV images were sent to the JPL control station over the NASA Select Satellite TV channel at video rate. Command and control data from JPL to GSFC and status and sensor data from GSFC to JPL were sent through the Internet computer communication network. The roundtrip command/information time delay varied between four to eight seconds between the GSFC worksite and the JPL control station.

The task involved the exchange of a satellite module. This required inserting a 45cm-long power screwdriver, attached to a robot arm, through a 45cm-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. Figure 3 illustrates two task segments of this satellite module exchange scenario in wire-frame format.

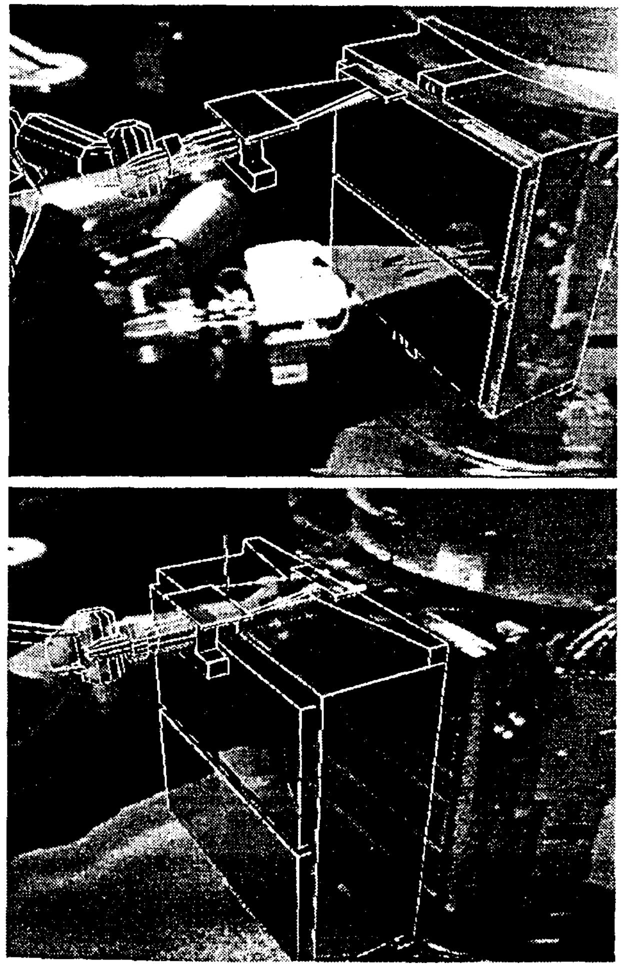

Figure 3. Computer graphics calibrated overlay robot allows operator instant feedback in spite of time delays

The experiments have been performed successfully. The calibration and object localization errors at the critical tool insertion task amounted to 0.2 cm each, well within the allowed error tolerance. More on this experiment and on performance details can be found in [3, 4]. (A narrated 12-minute JPL VCR tape is available on this experiment at the JPL Audio-Video Library, with I. D. No. AVC-93-165CID).

Recently, JPL established a technology cooperation agreement with Deneb Robotics, Inc. According to this agreement, JPL transfers the Virtual Reality (VR) calibration software technology to Deneb, and Deneb inserts it into its TELEGRIP™ commercial product, benefiting both space and terrestrial telerobotic applications. Evolving enhancements of this calibration technology are also planned to be added to the commercialized product.

The ongoing enhancement work includes the implementation of semi-automatic procedures using multi-resolution correlation-based area matching and edge-based feature matching techniques. These two techniques are complementary. Their use will automatically track and update robot arm or object position/orientation in the viewed task space during motion, provided that the displacements between two consecutive video image frames are small. More on this ongoing work in [5],

FUTURE PERSPECTIVES

The role of VR techniques in intelligent remote control of underwater vehicle and manipulator systems is nearly identical to the one outlined for general teleoperation in the introduction of this paper. Indeed, the possibility and utility of VR technology as an active operator interface modality in remotely controlled underwater vehicle /manipulator operation has already been demonstrated [6].

In the fall of 1993, NASA Ames Research Center (ARC) deployed a remotely operated vehicle under the Ross Sea ice near the McMurdo Science Station in Antarctica. The vehicle was also operated remotely, over a satellite communications link from a control room at ARC in California, using VR technology. The operator was able to view a computer-generated graphic representation of the underwater terrain, modeled from the vehicle's sensors. The virtual environment contained an animated graphic model of the vehicle which reflected the state of the actual vehicle, along with auxiliary information on the vehicle track, science markers, and locations of video snapshots. The actual vehicle was controlled either from within the VR or through a live telepresence interface (a head-mounted and head-tracked stereo display). More on this in [6].

The future perspectives could certainly include the broadening of the JPL-developed VR calibration techniques, briefly described in this paper, to underwater scenarios. The techniques could be adapted to underwater visual conditions, including the possible fusion of video and sonar images. The benefits of calibrated graphics overlays over video or over combined video-sonar images would be identical to the ones summarized in the introductory section of this paper.

ACKNOWLEDGMENT

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