Commercialization of JPL Virtual Reality Calibration and Redundant Manipulator Control Technologies

Won S. Kim
Homayoun Seraji
Paolo Fiorini

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
(818)354-5047
fax: (818)393-5007
wonsoo@telerobotics.jpl.nasa.gov

Robert Brown
Brian Christensen
Chris Beale

Deneb Robotics, Inc.
3285 Lapeer Road West
P. O. Box 214687
Auburn Hills, MI 48321-4687
(810)377-6900
fax: (810) 377-8125
bob@deneb.com

James Karlen
Paul Eismann

Robotics Research Corp.
P.O. Box 206
Amelia, OH 45102
(513)831-9570
fax: (513)381-5802

KEY WORDS AND PHRASES

Robotics, virtual reality, calibration, redundant robot arm control.

INTRODUCTION

Within NASA's recent thrust for industrial collaboration, JPL (Jet Propulsion Laboratory) has recently established two technology cooperation agreements in the robotics area: one on virtual reality (VR) calibration with Deneb Robotics, Inc., and the other on redundant manipulator control with Robotics Research Corporation (RRC). These technology transfer cooperation tasks will enable both Deneb and RRC to commercialize enhanced versions of their products that will greatly benefit both space and terrestrial telerobotic applications.

COMMERCIALIZATION OF JPL VIRTUAL REALITY CALIBRATION TECHNOLOGY

JPL recently developed a virtual reality (VR) calibration technique that enables reliable and accurate matching of a graphically simulated virtual environment in 3-D geometry and perspective with actual video camera views [1], [2]. This technique enables high-fidelity preview/predictive displays with calibrated graphic overlay on live video for telerobotic servicing applications. Its effectiveness was successfully demonstrated in a recent JPL (Jet Propulsion Laboratory)/NASA-GSFC (Goddard Space Flight Center) ORU (Orbital Replacement Unit) changeout remote servicing task. The current JPL VR calibration is a two-step procedure: camera calibration followed by object localization. Key new features of this

JPL VR calibration technique include: 1) an operator-interactive method adopted to obtain reliable correspondence data, 2) a robot arm itself used as a calibration fixture for camera calibration, eliminating a cumbersome procedure of using external calibration fixtures, 3) the object localization procedure added after the camera calibration to obtain graphic overlay of both the robot arm and the object(s) on live video enabling effective use of the computer-generated trajectory mode in addition to the teleoperation mode, 4) a projection-based linear least-squares algorithm extended to handle multiple camera views for object localization, and 5) nonlinear least-squares algorithms combined with linear ones employed for both camera calibration and object localization. Details of the algorithms and their software listings [3] were prepared as part of this JPL-Industry cooperative task.

An example of a calibrated graphic overlay after the virtual reality calibration for the JPL/NASA-GSFC remote servicing demonstration is shown in Figure 1. The positioning alignment accuracy achieved in inserting a tool into the ORU hole using 4 camera views was 0.51 *cm* on the average with a 1.07 *cm* maximum error at 95% confidence level. After matching 3-D graphics models of a virtual environment with actual camera views through the above virtual reality calibration technique, the operator can now perform a telerobotic servicing task with preview/predictive displays having calibrated graphics overlay on live video. Preview/predictive displays allow the operator to generate the simulated robot arm trajectory in preview and then to visually monitor and verify the actual remote robot arm motion with confidence, and thus provide
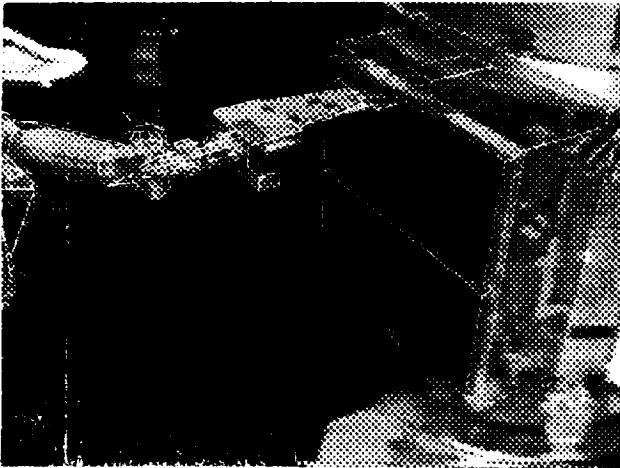
Figure 1: Overlay of calibrated 3-D graphic models (wire-frames with semi-transparent surfaces) on live video for telerobotic satellite servicing.
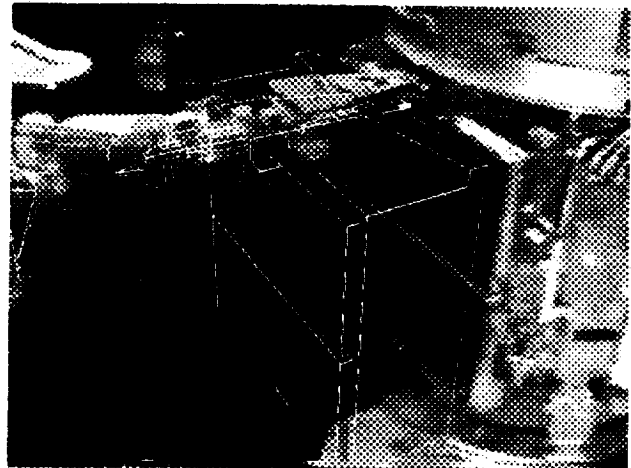

Figure 2: A snapshot of a preview/predictive display during the performance of the ORU extraction in the JPL/GSFC ORU changeout demonstration task.

effective visual prediction/verification to the operator and enhance safety and reliability in remote servicing operations regardless of communication time delay. Figure 2 shows a snapshot of a preview/predictive display during the performance of the JPL/GSFC demonstration.

Approach

We have taken the following approach in our JPL-Industry cooperative Deneb Commercialization Task: 1) JPL transfers the VR calibration software technology to Deneb, 2) Deneb, cooperating with JPL, inserts this software technology into its commercial product TELEGRIP as the video overlay/VR calibration option for marketing, and 3) in return, NASA utilizes this enhancement of a commercially supported product for NASA applications.

The virtual reality calibration option implemented on TELEGRIP will be an important element to build a state-of-the art VR interface in telerobotic applications with preview/predictive displays. Thus, the enhanced Deneb product can be effectively used in both space and terrestrial telerobotics applications, providing 1) immediate benefits to NASA for ground-controlled telerobotic servicing in space, 2) immediate benefits to the national DOE (Department of Energy) labs working on the disposal and remediation of nuclear waste, and 3) foreseeable potential applications in automotive manufacturing, medical telerobotic surgery, telerobotic construction, and maintenance robots.

Implementation on TELEGRIP

The JPL virtual reality calibration option is currently being implemented on Deneb's TELEGRIP [4] which is an open architecture based upon Dynamic Shared Objects (DSO's). DSO's provide many benefits when compared with other strategies for incorporating user-defined modules with a centralized kernel, including 1) speed of development, 2) access to all internal functions and data, including the entire geometric database, 3) flexibility in development, and 4) minimizing platform dependence. A key important feature provided by this TELEGRIP open architecture is that it allows developers/users to add their own virtual reality calibration algorithms and video overlay methods, if necessary.

Both one-window and two-window graphics/video displays are planned to be supported for VR calibration. Under the one-window calibration strategy, the TELEGRIP graphics display is divided into two separate vertically arranged NTSC-size (National Television Systems Committee standard) viewports. One viewport contains the live video image of the work environment, while the other displays the equivalent 3D graphical model. Upon completion of the camera calibration and object localization phases, the graphics-overlaid video image will be available to display in one of the viewports or to display on a separate NTSC monitor. The two-window approach relies upon two external NTSC-size GL (Graphics Library) or GLX (Graphics Library in X environments) windows with one window containing the live video image and the other the 3D graphic display. This enables users to relocate the

windows in a manner desirable for their particular application. Upon completion of the camera calibration and object localization phases, a graphics-overlaid video image is available to display in any window, including the TELEGRIP window, or to display on a separate NTSC screen.

The TELEGRIP video overlay implementation is based upon an application programmer interface (API) layer which insulates the overlay developer from the specifics of video hardware, thus enabling support over a wide range of video products. Support is currently planned for the SGI (Silicon Graphics, Inc.) VideoLab, Galileo, Indigo2, Indy, and Serius video boards encompassing the entire range of current SGI computing hardware from the Indy to the Onyx. Graphic models can be overlaid in wire-frame or in solid-shaded polygonal rendering, with varying levels of transparency to produce different visual effects.

COMMERCIALIZATION OF JPL REDUNDANT MANIPULATOR CONTROL TECHNOLOGY

Theoretical and experimental investigations have demonstrated that dexterous manipulation tasks can be carried out only by redundant, force-controlled robotic manipulators that possess flexibility and versatility comparable to the human arm. For research in this area, the Robotics Laboratory at JPL acquired in 1989 two redundant 7-DOF (degree-of-freedom) manipulators made by Robotics Research Corporation (RRC) of Ohio, the leading manufacturer of this type of manipulators since the mid 1980's.

At the time of purchase, neither the application domain nor the required redundant control laws for such advanced manipulators was fully developed. JPL research has contributed to both areas by identifying tasks in which redundancy is essential and by developing an underlying control methodology for such manipulators.

RRC has recently expanded and enhanced its product line by introducing a second-generation version of its manipulator that provides improved mechanical performance and employs a unique low-level control system in which all servo electronics are mounted in the arm. It is now logical to begin integrating RRC's state-of-the-art servomechanism technology with JPL's advanced high-level control developments, and to prepare this new robot technology for commercial applications.

Under funding from NASA, the first phase of such a commercialization activity began in FY'94, with the transfer to RRC of an algorithm for redundant arm control developed at JPL[5-9] and widely used in the robotics community. This algorithm, known as Configuration Control, combines the specification of a set of constraint tasks with the end-effector prescribed trajectory to provide a highly efficient and powerful redundant arm control strategy.

Background

During the course of the past two years, RRC has developed a unique servo control architecture for its manipulator arms which greatly reduces the need for expensive external power and computing electronics and replaces the costly internal arm wiring harness with a "fly-by-wire" data/power bus communication system. Miniature DSP (Digital Signal Processor)-based servo control modules, containing all computing and power electronics, are collocated with the joint actuators in the manipulator arm joints. The parameters for the individual joint controllers are downloaded by a master computer via a high-speed communication link. Since the remotely-located master computer is free from the burden of servo power and computing electronics, high-level control functions can now be practically transferred to a general-purpose workstation or personal computer with significant cost savings. This new high-level RRC controller is designated the Next Generation Controller (RRC/NGC).

In the area of redundant arm control, JPL has developed a class of motion control algorithms for redundant manipulators called Configuration Control (CC),[5-9]. In this approach, the user can specify task-dependent constraints for the redundant manipulator which have the effect of utilizing the robot redundancy and allowing efficient end-effector trajectory control. Since this approach was implemented originally on RRC manipulators and the resulting algorithms were extensively tested in several experiments, it is felt that this technology is mature enough to be transferred to industry and incorporated into RRC's new product line (see Figure 3).

The RRC/NGC system under development will be highly compatible with the kind of centralized high-level control embedded in the CC approach. The master computer used in the NGC system is a standard workstation, and it is well suited to run the CC algorithms. Furthermore the use of a workstation (or of a PC) as a master computer enables RRC to make use of enhanced graphic capabilities to provide the user with a sophisticated interface for motion planning and control.

Approach

In order to ensure that the technology transfer proceeds smoothly, the following steps have been planned:

1. Duplicate the hardware and software environment of the RRC/NGC at JPL and test it with
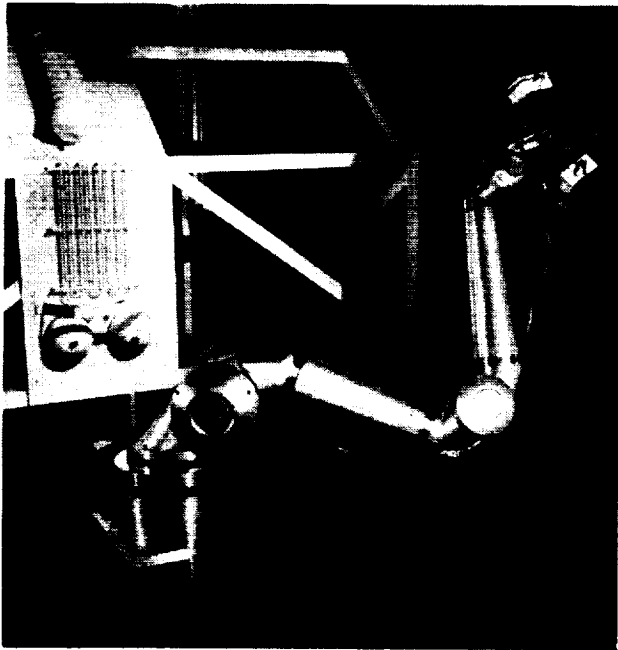
Figure 3: 7-DOF Robotics Research arm.

the RRC manipulators in the JPL Robotics Laboratory.

2. Modify JPL Configuration Control algorithms to make them compatible with the NGC environment, implement and test the algorithms on the master computer adopted in the NGC system and with the current RRC manipulators in the JPL Robotics Laboratory.

3. Integrate the tested algorithms with the new RRC manipulators using the Next Generation Controller.

Technology Transfer Issues

A technology transfer task of this type requires the same steps as to transform a laboratory prototype into a commercial product. Once the functionality of the prototype, the CC algorithms in this case, has been established and verified, then the development efforts must focus on issues such as compatibility with the rest of the system, price/performance trade-off, documentation, maintainability, and so on.

The decision was made by RRC to implement as much as possible of their software in object-oriented format, and use an IBM-compatible personal computer as the master controller. From the JPL side, it was necessary to re-engineer some existing software to eliminate the dependency of the code on data structures related to the rest of the JPL system, and to port the programs to an operating system compatible with the IBM-PC that RRC has selected as its NGC platform. In the

interest of compatibility with existing RRC software, as well as to minimize overall system cost, the real-time operating system selected is the Intel iRMX running under Windows, which can execute RRC's existing code as well as the new JPL Configuration Control software modules.

The technology transfer is currently proceeding smoothly and most of the necessary programs have already been converted to a stand-alone configuration. We will be ready to integrate this software with the PC-based real-time system and test it with the RRC redundant manipulators in the JPL Robotics Laboratory later this year.

ACKNOWLEDGMENT

REFERENCES

[1] Kim, W. S., Schenker, P. S., Bejczy, A. K., Leake, S., and Ollendorf, S., 1993. "An Advanced Operator Interface Design with Preview/Predictive Displays for Ground-Controlled Space Telerobotic Servicing," SPIE Conference 2057: *Telemanipulator Technology and Space Telerobotics*, 96-107, Boston, MA.

[2] Kim, W. S. and A. K. Bejczy, 1993. "Demonstration of a High-Fidelity Predictive/Preview Display Technique for Telerobotic Servicing in Space," *IEEE Trans. on Robotics and Automation*, 9(5), 698-702.

[3] Kim, W. S., 1994. *Virtual Reality Calibration: Algorithms and Software Listings with an application to Preview/Predictive Displays for Telerobotic Servicing*, JPL D-11593 (Internal Document), Jet Propulsion Laboratory, California Institute of Technology.

[4] Deneb Robotics, Inc., 1994. *TELEGRIP Access Reference Manual.*

[5] Seraji, H., 1989. "Configuration Control of Redundant Manipulators: Theory and Implementation", *IEEE Transactions on Robotics and Automation*, 5(4), 472-490.

[6] Seraji, H. and R. Colbaugh, 1990. "Improved Configuration Control for Redundant Robots", *Journal of Robotic Systems*, 7(6), 897-928.

[7] Colbaugh, R., H. Seraji, and K. Glass, 1989. "Obstacle Avoidance for Redundant Robots Using Configuration Control", *Journal of Robotic Systems*, 6(6), 721-744.

[8] Seraji, H., 1992. "Task-Based Configuration Control of Redundant Robots", *Journal of Robotic Systems*, 9(3), 411-451.

[9] Seraji, H., M. Long, and T. Lee, 1993. "Motion Control of 7-DOF Arms: The Configuration Control Approach", *IEEE Transactions on Robotics and Automation*, 9(2), 125-139.