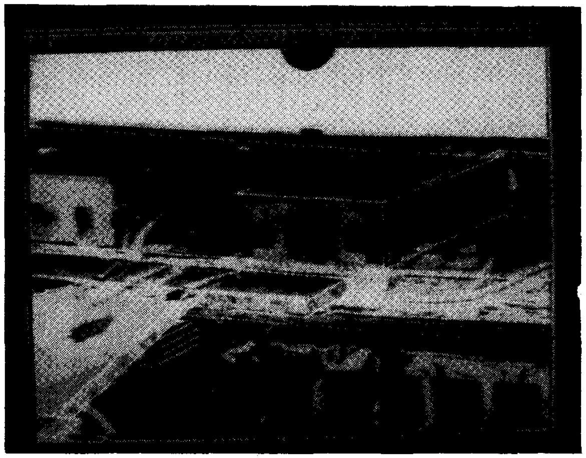

Fig. 6. Same configuration and TV camera view as in Fig. 5, but camera zoomed in.

0.8% average error corresponds to 0.5 cm displacement error on the plane 1 m in front of the camera. For the zoom-in view ($fovy = 8°$), the average error on the image plane was typically 1.2-1.6% (3.2-4.2% maximum error), and the 1.4% average error corresponds to 0.2 cm displacement error on the plane 1 m in front of the camera (See Fig. 6 for this setting).

The average object localization errors on the image planes were about 0.9-1.9% (3.0–7.0% maximum errors). The 1.4% average error on the image planes corresponds to 0.2 cm displacement error with respect to the zoom-in overhead camera view, and to 2.5 cm displacement error with respect to the side-view or oblique-view cameras, in wide field-of-view settings.

V. CONCLUSION

The demonstration experiments have been performed successfully, showing the practical utility of high-fidelity predictive/preview display techniques, combined with compliance control, for the type of telerobotic servicing tasks in space that were shown in the May, 1993 demonstration. The same techniques also have a wide range of terrestrial application possibilities. Future work will include: 1) simulated tests on other space application tasks like Hubble Space Telescope Servicing, and 2) interactive model building and intermittent model matching updates using model-based image processing.

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Network-Based Infrastructure for Distributed Remote Operations and Robotics Research

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Abstract—**The establishment of a unique infrastructure for distributed robotics and remote operations research within an educational environment is reported. Using a new object-oriented protocol (TelRIP) and Internet, this distributed laboratory consists of sites at four universities (Universities Space Automation and Robotics Consortium) and NASA's Johnson Space Center. The distributed laboratory configuration provides the opportunity to quantitatively study the effects of various system components and technologies on overall telerobotic task performance. We have successfully implemented and demonstrated (first in February 1991) the ability to execute representative inspection and manipulation tasks with multiple control, robot, and performance/workload monitoring sites simultaneously connected. Operations are carried out on a routine basis. During the process, needs for hardware and software standards development have been identified. The current implementation provides the basis to link government, industrial, and university facilities to realize a truly collaborative research and development environment, enabling graduate students to experience rich educational opportunities that would otherwise not be possible.**

I. INTRODUCTION

Few facilities exist that represent a suitable environment for the development and evaluation of the components, protocols, and operational modes needed for a complete telerobotics system. As such, the robotics research community has been slow to address systems integration issues and assess the impact of component technologies. Furthermore, the technology for creating such environments

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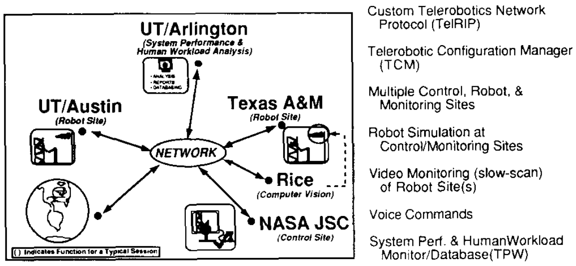

Fig. 1. Summary of the environment for distributed remote operations and robotics research.

is relatively immature. Those capabilities that do exist have been used in point-to-point remote operations and other related experiments [1–3] and have proven to be useful research environments. However, space applications (e.g., ground-based control), ground-based applications (e.g., hazardous operations), and the ground-based development process (including evaluations) require system configurations with greater degrees of freedom, i.e. connectivity of multiple sites with different functions. With regard to development, it is desirable to link government, industrial, and university facilities so that a collaborative research and development environment can be realized with associated sharing of unique resources to enhance the educational setting available to graduate students.

Over the past three years, research groups from the authors' four universities (collectively forming an organization known as the Universities Space Automation and Robotics Consortium, USARC) have collaborated with staff and contractors at NASA's Johnson Space Center (JSC) to create and utilize a distributed telerobotics laboratory. Since USARC's beginning, students and staff have worked together to design and integrate new "enabling" components with existing telerobotic technologies. Capabilities developed include: 1) an object-oriented communications protocol (TelRIP) [4] to provide network connections among participants, 2) network interfaces for a variety of control, sensing, and manipulation devices across geographically separated sites, 3) strategies for time-delay tolerant operations, 4) techniques for measurement, real-time monitoring, logging, and databasing of human workload and overall telerobotic system performance, and 5) a telerobotic configuration manager, ultimately intended to enable optimal use of networked resources.

II. Laboratory Configuration

USARC's distributed laboratory consists of control, robot, and monitoring nodes distributed over a wide area (see Fig. 1). Although Internet has been the primary means of communication, it is relatively straightforward to use alternate communication modes. For example, both modem and satellite connections have been used along with Internet. Bandwidth and delays associated with Internet [5] do not limit our control and monitoring objectives (control of a robot at JSC from Japan has been successfully demonstrated) and, in fact, force efficient resource utilization.

Tasks involving primarily manipulation (e.g., removal and replacement of a space station orbital replacement unit (ORU)) and primarily visual inspection have been performed. A network session for the latter is described below, with annotations to illustrate the collaborative nature of both the development and operation:

> Five sites sign-on to the network using TelRIP (developed by Rice), which provides the required connectivity. From JSC (control site), visual inspection of a truss located at Texas A&M (robot site) is performed using robot control code developed by UT Austin personnel. At the control site, a combination of manual control and voice commands are used. A workstation display provides the operator with a simulation as well as slow scan video frames (up to 5–7 frames/s) of robot activity and the truss environment A puncture in the cover of a control panel on the truss is first identified visually. Then, using code to implement autonomous inspection (developed by Texas A&M), the cover is removed and the robot returns to inspect the region behind the cover. Inspection views of the truss interior are generated for review at the control site. All network data is logged and processed (with code developed by UT Arlington) at UT Arlington (the primary monitoring site). Measures of operator workload and overall telerobotic system performance are computed. UT Arlington sends periodic reports and a final "Session Report" over the network to other sites (secondary monitoring sites) running monitoring code in a "display only" mode. Raw data and parameterized workload/performance measures are databased at the primary monitoring site.

Remote control of remotely located telerobotic hardware (e.g., robots, camera, sensors) over a network with significant variable time delays emulates conditions that will exist in ground-controlled space operations. We have implemented "time clutch" and "position clutch" controls [6] to minimize the adverse impact of time delays and intend to evaluate these and other possible solutions in different task contexts. The Consortium is also incorporating strategies for achieving fault-tolerance [7] into components that comprise the laboratory environment.

III. Experiments

Three classes of experiments are carried out in the distributed telerobotics laboratory: 1) functional evaluation, 2) robustness, and 3) question-specific. Although the "quesiton-specific" type are the most rigorous from an experimental design perspective, data (configuration, workload, and performance) is databased for each experiment regardless of type. Functional evaluations are more general and aimed primarily at identifying connectivity, protocol, and integration problems; they provide results that are largely qualitative. However, recorded data is useful for analysis of task timelines for use in the planning and refinement of operational sequences. To demonstrate and test robustness, two-hour network sessions have been held weekly (January–April 1993) and are currently held biweekly. These sessions provide the opportunity to test software updates and new functional capabilities being developed to support functional evaluation or focused experiments. Moreover, they provide the opportunity to create a sense of confidence in remote operations technology.

Question-specific experiments are designed to address questions such as, "How is overall system performance affected by different manual controllers for a given class of operational tasks?" Here, special tasks are designed according to a maximal demand strategy [8], which is incorporated into very formal data collection sessions. Measures of overall system performance (e.g., speed, accuracy, and smoothness) are computed solely from end-effector position samples and quantitative attributes of the task environment. We are not only concerned with the overall performance that can be achieved with a given configuration but also with the workload imposed on the operator that is associated with a given level of performance in a given task. Neuromotor workload measures (as a function of time and parameterizations), derived from manual controller channels, are computed. Measures of visual information workload are under development.

We anticipate that this experimental emphasis (in which every session is treated as a data-producing experiment) will help standardize the means used to characterize configurations and tasks, and to evaluate system performance, thereby facilitating objective cross-comparisons. The regular cataloging of session data provides the opportunity for retrospective studies that look across multiple experiments to answer new questions without the need to generate new data. It also aids in efficient planning of experiments to fill in gaps in knowledge. Issues relating to the effects of operator training, different manual controllers and control modes (e.g., force reflection, degree of autonomous control), different visual feedback schemes, and estimates of time-lines for new operations are all topics for which relatively little quantitative data currently exists.

IV. CONCLUSION

The distributed laboratory approach has been found to be a rewarding, cost-effective means for conducting collaborative work in a rich research environment made possible predominantly through the sharing of unique resources (both human and technologic). It affords students within each university's program to participate in what is believed to be a unique opportunity for multidisciplinary cross-fertilization and the ability to undertake research projects of a nature that would otherwise not be possible. The approach has also contributed to a revitalization of the space program presence within university environments (particularly in engineering), which has been noticeably diminished in recent years. This type of activity serves as a means to recruit, train, and produce a new generation of individuals capable of contributing to the infrastructure and future of the space program.

The current implementation provides an excellent base upon which additional capabilities can be built and experiments conducted. While motivated by the demanding requirements of space applications, the technology developed to create this environment has direct application to a multitude of Earth-bound commercial domains, such as waste site clean-up and maintenance of offshore petroleum industry facilities from onshore sites.

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