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THE VIRTUAL ROBOTICS LABORATORY*

R. L. Kress
Oak Ridge National Laboratory
Robotics and Process Systems Division
P. O. Box 2008
Oak Ridge, Tennessee 37831-6426
(423) 576-2468

L. J. Love
Oak Ridge Institute for Science and Education
P. O. Box 2008
Oak Ridge, Tennessee 37831-6426
(423) 576-4630

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ABSTRACT

The growth of the Internet has provided a unique opportunity to expand research collaborations between industry, universities, and the national laboratories. The Virtual Robotics Laboratory (VRL) is an innovative program at Oak Ridge National Laboratory (ORNL) that is focusing on the issues related to collaborative research through controlled access of laboratory equipment using the World Wide Web. The VRL will provide different levels of access to selected ORNL laboratory equipment to outside universities, industrial researchers, and elementary and secondary education programs. In the past, the ORNL Robotics and Process Systems Division (RPSD) has developed state-of-the-art robotic systems for the Army, NASA, Department of Energy, Department of Defense, as well as many other clients. After proof of concept, many of these systems sit dormant in the laboratories. This is not out of completion of all possible research topics, but from completion of contracts and generation of new programs. In the past, a number of visiting professors have used this equipment for their own research. However, this requires that the professor, and possibly his students, spend extended periods at the laboratory facility. In addition, only a very exclusive group of faculty can gain access to the laboratory and hardware. The VRL is a tool that enables extended collaborative efforts without regard to geographic limitations.

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I. INTRODUCTION

A. Description

The Virtual Robotics Laboratory (VRL) concept is envisioned as a way to increase the efficiency and cost-effectiveness of collaborating robotic research laboratories.

Basically, the virtual laboratory concept is an electronic linking of laboratories, computers, data bases, equipment, personnel, etc., at various locations geographically distributed throughout the world. Linking is done via a high-performance, stable, low-cost networking infrastructure. The connections are made so that information, data, experimental results, algorithms, papers, etc., may be efficiently exchanged and shared by researchers. These connections will not only facilitate data exchange but will also allow for remote experiments to be performed by researchers physically located far from a laboratory facility.

The purpose of the VRL is to provide laboratory facilities/user facilities to the university community, community college systems, industry, and other national laboratories for the development of robotic professionals. Many experiments planned at universities, as well as other national or industrial laboratories, can be done with hardware that presently exists at ORNL Robotics and Process Systems Division. The hardware at ORNL RPSD is too expensive to establish or maintain at the individual institutions. The VRL would have two goals. Initially, the VRL would allow researchers to develop theories, models, control algorithms, new robotic systems, etc., at their institutions and transfer the ideas, algorithms, designs, etc., to ORNL, where they can be implemented, verified, improved, and refined using the existing hardware infrastructure located at ORNL and applied to Department of Energy (DOE) problems. Eventually, the VRL will provide robotics-related

laboratory facilities for the development and enhancement of science curriculum at all educational levels.

An example of the need for a VRL can be seen in the context of the Robotics Technology Development Program's (RTDP's) effort to perform the decontamination and dismantlement (D&D) on the CP-5 reactor at Argonne National Laboratory (ANL). The CP-5 reactor was used as an experimental reactor for many years beginning in the 1950s and is presently decommissioned. DOE has been developing dual-arm manipulators for dismantlement, and recently a need arose to evaluate ANL personnel as potential operators and to assess their ability. Experiments with existing teleoperated manipulators were planned, but execution of the experiments will take months because the manipulator systems are located at ORNL RPSD. Had the VRL existed, the experiments and the assessments could have been completed in a few days without any travel by using the worldwide network. In addition, training sessions for those people needing to improve their skills could be planned and executed over the network, and skill level and timing data could be shared with researchers at other national laboratories and universities. Figure 1 illustrates the relationship between the present state of Web applications and the VRL research outlined in this proposal. Present web applications rely on simple interfaces and very little information feedback. The VRL will be able to operate in this manner, but it will also be capable of much greater levels of performance based on the needs and desires of the participating researchers, students, and industry and government personnel.

B. Background

Over the past decades, DOE has spent millions of dollars developing robotics and remotely operated hardware for use in hazardous environments. Many of these systems are resident at the national laboratories. As an example, consider the ORNL RPSD Robotics Technology Assessment Facility (RTAF). This facility contains a control room, a dual-arm manipulator system, mobile robots, process system mockups, vision systems, heavy-lift transporters, and numerous computers. Some of the equipment in this facility has been under development since the early 1980s, and its total worth is tens of millions of dollars. RPSD has similar facilities including other dual arm remote manipulator systems, hydraulic manipulator laboratories, automated material handling facilities, and simulation resources that have been funded by DOE, the Department of Defense (DOE), the National Aeronautics and Space Administration (NASA), and others for years. Together, these facilities represent a major hardware, software, and experience base that is all applicable to numerous research challenges in the environmental restoration and cleanup areas. When other National Laboratories are considered, DOE's investment in robotics facilities for hazardous environments is staggering, certainly exceeding several hundred million dollars. Presently, access to these facilities is limited to DOE personnel and a very select few university researchers who work directly with national laboratory projects. Limiting access as such greatly reduces the effectiveness and usefulness of the existing facilities and results in what is, at best, significant inefficiencies and, at worst, lack of research and development in particular areas. Providing greater access to these facilities efficiently utilizes and applies this robotics infrastructure to the solution of fundamental research problems. Example problems may include remote handling, environmental restoration and cleanup, and also the solution of advanced robotics research problems.

The basic elements of a VRL are beginning to appear in recent robotics literature. Consider the recent placement of a robotic excavation system on the World Wide Web (WWW) by the University of Southern California.[1,2] Named the Mercury Project, it was the first system that allowed WWW users to remotely view and alter the real world by using a telerobot. The Mercury Project operated for seven months (from September 1, 1994, to March 31, 1995) and received over 2.5 million hits. The same team is now offering a telerobotic gardening system over the WWW. Other institutions have also placed robots on the Web[3,4] as well as other research equipment such as telescopes.[5] Another example of the use of the WWW for remote robotics applications consisted of transmitting experimental data in real time from an Atlanta-based flexible manipulator system to a robotics technology forum in Albuquerque.[6] This demonstration included an animated display of the robot conducting an experiment as well as a live video feed using the CU-SeeMe software developed by Cornell University. The effectiveness of a remote system run over the Internet was recently published with regard to multimedia telesurgery.[7,8]

Software developments for modular robotic systems have paralleled the introduction of robotic hardware on the WWW. Examples include the Sequential Modular Architecture for Robotics and Teleoperation[9] and Control Shell.[10-12] Time delay problems[13] and generalized telerobotic interfaces[14] have been previously addressed as well as control of ORNL RTAF facility hardware over the network and with modular software.[15] "Plug and play"-type demonstrations mixing hardware and software have also been demonstrated and could be applied to a VRL implementation.[16]

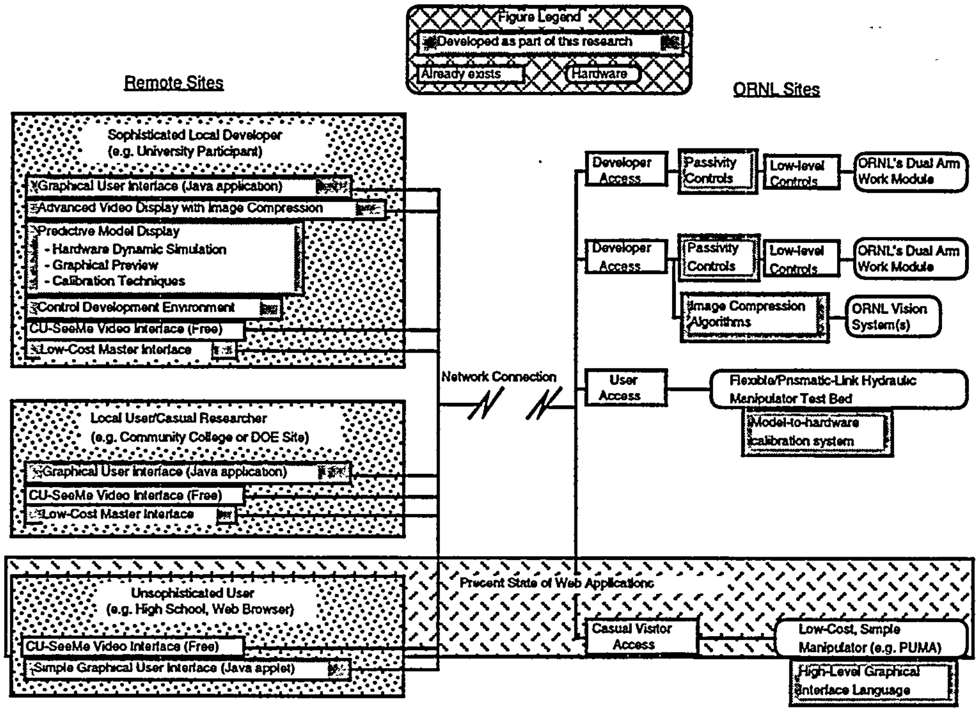

Figure 1: Relationship between the present state of web applications and the VRL

II. APPROACH

A. General VRL Concept

Figure 2 illustrates one concept of the possible form the VRL might eventually take in its more mature phases.

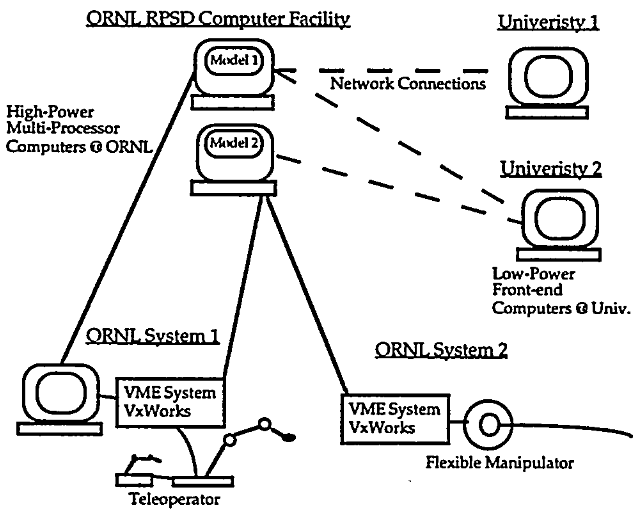

Figure 2. Schematic of a Virtual Robotics Laboratory concept

Figure 2 also shows a schematic of the VRL concept as it might be generally implemented between ORNL and different universities. ORNL would develop and maintain multiple robotic systems such as teleoperators, robots, mobile vehicles, vision systems, etc. Computer facilities at ORNL would be used to support the hardware, including high-performance, multiprocessor computers for modeling and control. Software packages and capability at ORNL support the VRL as well. Controls development software such as Control Shell, MatrixX, and MATLAB can be interfaced with dynamics modeling software packages such as Automatic Dynamic Analysis of Mechanical Systems (ADAMS), Dynamic Analysis and Design System (DADS), and Interactive Graphical Robotic Instruction Program (IGRIP).

A college, university, industry, or other national laboratory scientist would participate in the VRL as outlined in the set of steps below.

1. Development will be done by professors, scientists, and/or students using remote-located, possibly deep-discounted versions of software or by remotely running software resident at ORNL when allowed by license agreements. Some development would involve the use of large models developed over several years at ORNL [e.g., large waste storage tank, Modified Light-Duty Utility Arm (MLDUA), and

Waste Dislodging and Conveyance (WD&C) models currently under development for the Gunite tank remediation].[17]

2. Theories, algorithms, models, etc., can be transferred via the network to ORNL, where hardware facilities exist [e.g., Dual-Arm Work Module (DAWM), ROSIE® mobile robotic base, the Schilling Multi-Degree-of-Freedom Flexible Manipulator, the ORNL Flexible/Prismatic-Link Manipulator].
3. ORNL researchers in cooperation with the university, industry, or other national laboratory researchers test and evaluate the new product. The VRL participants can remain at their remote sites if desired.
4. The developed product is transferred back to the participating institution for further refinements and developments at the remote site.
5. Repeat steps 2 through 4 until the new product is mature.
6. Institute personnel travel to ORNL for final tests, evaluations, refinements, etc., on their product. Research is done in cooperation with ORNL staff.

B. Overall Task Description

Basically, the virtual laboratory concept is an electronic linking of laboratories, computers, data bases, equipment, personnel, etc., at various locations geographically distributed throughout the world. Linking is done via a high-performance, stable, and low-cost networking infrastructure. The connections are made so that not only are information, data, experimental results, algorithms, papers, etc., exchanged and shared by researchers, but also so that a virtual physical presence is established. This virtual physical presence is not only limited to video and sensory feedback but also includes physical data and process data feedback to appropriate interfaces such that a mechanical presence is established. Providing the necessary mechanical interface system theory and hardware; developing appropriate software architectures that provide modularity, portability, and stability; and solving fundamental problems such as control latency are some of the basic research challenges restricting the implementation of a true VRL. The connections established within a VRL network will not only facilitate information and data exchange but will also allow for remote experiments, demonstrations, system trials, training, etc., to be performed by researchers, educators, environmental workers, plant managers, and others physically located far from a laboratory facility.

III. RESULTS

A. "Quick Hit" Tasks for the Near-Term VRL Concept

The DOE national laboratory system is a perfect setting for the introduction, implementation, and successful use of the virtual laboratory concept. To introduce the virtual laboratory concept and to establish credibility of the concept within DOE, some "quick hit" demonstrations are desirable. These demonstrations would illustrate certain virtual laboratory concepts as well as highlight current capabilities of the national laboratories that are particularly suitable for the virtual laboratory paradigm. These quick hit demonstrations are targeted to provide results within 1 year of initiation. These quick hits provide insight into possible problems in areas that need careful research in the remaining contract period. They will not, however, be wasted effort in that they will form a basis for the long-term tasks that follow. These three quick hit tasks are broken up into fundamental elements of the VRL. First, a task is defined that establishes the basic unilateral information flow between the VRL and the remote user. The second task focuses on providing the ability to let the remote user interact with the VRL and modify his/her local representation of the VRL "world." Finally, the third task addresses bilateral information flow between the VRL and the remote site which affords the remote "operator" more direct control over his/her interaction with the local (ORNL) site. This brief write-up describes some of the proposed quick hit ideas.

1. Dynamic Simulation-Based Preview Control: This demonstration would use an ORNL-based automated system to perform a task that is conceived and commanded remotely. The ORNL system might be an automated process line, a robot, a teleoperator, etc. The task steps will be previewed remotely using a simulation containing dynamics that accurately model the important physical attributes of the ORNL system. If the task is safely completed in simulation, then the commands are relayed to the remote system and the task is executed. If the remote simulation shows that the task fails, then the operator is notified and the task is not executed on the ORNL hardware. After the task is executed, hardware status is returned to the remote user and the simulation is modified as necessary to match the existing physical situation at ORNL.

2. Task Space Metrology Used to Update Models (Remote Calibration): This demonstration focuses on the need to accurately calibrate models to the real system. This would be especially true for models representing remote facilities that might never have been seen by the local operator. In this demonstration, a local model of a remote facility exists. Data are collected from the remote facility to be used to calibrate a task space model. The data are transferred to the local operator, who then runs

reactor D&D) would need to use the hardware and expertise at each of these laboratories. This would be made possible by the VRL concept.

IV. FACILITIES

A. Oak Ridge National Laboratory

1. Dual-Arm Work Module (DAWM): The DAWM consists of two 6-D.O.F. Schilling Titan II hydraulic manipulators mounted to a 5-D.O.F. hydraulic positioning base that was designed and built for ORNL by RedZone Robotics, Inc.[19] The DAWM base motions provide for a 7-D.O.F. at the base of each Titan II so that manipulation can be approached in an elbows-up, elbows-out, or elbows-down configuration, depending on the task at hand. These rotary actuators have a ±90° rotation from the horizontal position. An elbows-up configuration is advantageous for operation from above on horizontally configured equipment. An elbows-down configuration is advantageous for working on vertically stacked equipment. The elbows-out positions allow the manipulators to reach around obstacles, if required. Two linear actuators locate the base of the arms anywhere between a separation of 24 to 60 inches. A center rotary actuator provides a ±90° rotation of the entire torso from the horizontal position, maximizing flexibility of the DAWM manipulation capabilities. These positioning capabilities allow the manipulators to be configured to the best pose for performing tasks in the cluttered and constrained environments expected during D&D activities.

2. The Flexible/Prismatic-Link Manipulator Test Bed: Control of flexible manipulators has been an active research topic for the past 20 years;[4] however, the majority of this work has focused on single-link, single-degree-of-freedom, rotary joint manipulators. However, a survey of industrial long-reach manipulators shows that most have hydraulic actuation, multiple degrees of freedom, and some prismatic joints. The flexible/prismatic-link manipulator (FPLM) test bed is a unique research manipulator designed, developed, and built at ORNL.[23] This test bed provides many interesting contrasts to existing flexible link research test beds. The majority of industrial long-reach manipulators use hydraulic cylinders and motors for the primary source of power. This is not by accident. Hydraulic actuators provide many interesting advantages over electromagnetic motors.[24] First, the circulating hydraulic fluid provides a natural source for both lubrication and heat dissipation. Higher loop gains and bandwidths are possible with hydraulic actuators. In addition, hydraulic actuators may be operated under continuous, intermittent, reversing, and stalled conditions without damage. In spite of these advantages, research in hydraulic manipulators has been slow in the past two decades. A second interesting observation is that most existing flexible link test beds contain only rotary joints while many industrial arms have prismatic degrees of freedom. Unfortunately, very little research has been conducted on the control of flexible links with prismatic joints. This configuration can provide an interesting complication in the control of flexible link manipulators. First, the natural frequency of the elastic link can vary dramatically over a very short range of motion. Furthermore, gravitational loads can produce a self-generated amplitude- and frequency-varying wave by simply retracting the link. ORNL may have the only full-scale, hydraulically actuated, flexible/prismatic-link manipulator test bed in the world. This robot currently has two hydraulically actuated degrees of freedom. The first degree of freedom is a rotary joint, while the second degree of freedom is a prismatic joint that extends a long slender link. With a 25 lb payload, the first mode of vibration can range from 45 to 1.5 Hz. This dramatic shift in natural frequencies can occur over a very short period of time. Interesting research topics that are anticipated include adaptive filtering and input shaping of time-varying dynamic systems, force control of elastic systems with varying dynamics, as well as end point control.

3. The Schilling 7F Flexible-Link Test Bed: A hydraulics test stand exists in ORNL RPSD's hydraulics laboratory that includes a Schilling 7F manipulator outfitted with a single flexible link.[25] Because a base system can cost as much as $150,000 for the hardware alone, only a select few institutions can financially afford a Schilling Titan 7F as an active research tool. Presently, the hydraulics laboratory at ORNL has a Titan 7F that has been outfitted with an additional flexible link between the wrist yaw and roll joints. This test bed captures a number of interesting problems in vibration control. Unlike many flexible robot test beds, the Titan 7F's flexible link has a moving and rotating base. Furthermore, the link is symmetric and can vibrate simultaneously in two planes of motion. The gripper on the end of the elastic link permits grasping and moving different payloads. This has a dramatic effect on the natural frequency for the links.

4. The Cold Test Facility: One of the premier robotics programs in the world is the Gunite and Associated Tanks (GAAT) program at ORNL.[17] This aggressive project consists of developing a method of using advanced robotics to extract hazardous materials out of underground storage facilities. This method consists of using an MLDUA in concert with a WD&C manipulator system. This combined system will move a confined sluicing end-effector around the interior of the waste tank,

extracting material for storage in a safer environment. Before the system is deployed in a real waste facility (planned for March of 1997), tests will be conducted in the Cold Test Facility at the RPSD in ORNL. The Cold Test Facility is a mockup of an underground storage tank. This facility includes a number of cameras inside the tank as well as realistic obstacles encountered inside the actual tanks. This facility will permit a safe avenue for operator training and testing of the deployment system, the MLDUA, the WD&C system, as well as the hardware used for the tank remediation project. These tests are planned to be conducted from November 1996 to March 1997.

5. The Robotics Simulation Laboratory: A number of high-speed computer systems, including an SGI Onyx workstation, as well as advanced simulation software tools are readily available for use. Presently, RPSD has scientists/engineers familiar with the following packages: MATLAB, Mathematical, MatrixX, DADS, ADAMS, IGRIP, TELEGRIP, micro-SAINT, and custom codes for calibration, system identification, control system development, and modeling of one-of-a-kind, highly nonlinear systems. These software packages are available in the simulation laboratory and represent a significant investment in software infrastructure.

V. CONCLUSIONS

The growth of the Internet and resurgence of robotics research have primed the incentive to develop collaborations via VRL. This paper has provided a rough sketch of what a VRL may look like. In addition, we have shown that many issues such as time delays and safety protocols remain open research issues. ORNL has a substantial inventory of robotic research tools. Our intent is to release these tools to the research community through an interface via the Internet.

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