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DUAL ARM WORK MODULE DEVELOPMENT AND APPLICATIONS*

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ABSTRACT

The dual arm work module (DAWM) was developed at Oak Ridge National Laboratory (ORNL) by the Robotics Technology Development Program (RTDP) as a development test bed to study issues related to dual arm manipulation, including platform configuration, controls, automation, operations, and tooling. The original platform was based on two Schilling Titan II manipulators mounted to a 5-degree-of-freedom (DOF) base fabricated by RedZone Robotics, Inc. The 5-DOF articulation provided a center torso rotation, linear actuation to change the separation between the arms, and arm base rotation joints to provide "elbows up," elbows down," or "elbows out" orientation. A series of tests were conducted on operations, tooling, and task space scene analysis (TSSA)-driven robotics for overhead transporter-mounted and crane hook-deployed scenarios. A concept was developed for DAWM deployment from a large remote work vehicle, but the project was redirected to support dismantlement of the Chicago Pile #5 (CP-5) reactor at Argonne National Laboratory in fiscal year (FY) 1997. Support of CP-5 required a change in focus of the dual arm technology from that of a development test bed to a system focussed for a specific end user. ORNL teamed with the Idaho National Environmental Engineering Laboratory, Sandia National Laboratory, and the Savannah River Technology Center to deliver a crane-deployed derivative of the DAWM, designated the dual arm work platform (DAWP). RTDP staff supported DAWP at CP-5 for one FY; Argonne staff continued operation through to dismantlement of the reactor internals. Lessons learned from this interaction were extensive. Beginning in FY 1999, dual arm development activities are again being pursued in the context of those lessons learned. This paper describes the progression of philosophy of the DAWM from initial test bed to lessons learned through interaction at CP-5 and to the present investigation of telerobotic assist of teleoperation and TSSA-driven robotics.

Introduction

The dual arm work module (DAWM) was developed at Oak Ridge National Laboratory (ORNL) by the Robotics Technology Development Program (RTDP) as a development test bed to study issues related to dual arm manipulation, including platform configuration, controls, automation, operations, and tooling. These activities were conducted under the Deactivation and Decommissioning (D&D) Focus Area robotics product line. The RTDP has since been renamed the Robotics Crosscut (RBX) Program. Generally, the time line of the DAWM can be divided into three eras: initial development, Chicago Pile #5 (CP-5) deployment, and current development.

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Initial DAWM work was based on knowledge gained through a foundation of teleoperation work done at ORNL in the 1970s and 1980s with the first digitally controlled master-slave, force-reflecting teleoperator, the M-2, and the first remotely maintainable force-reflecting teleoperator, the advanced servomanipulator (ASM).[1] In addition to pure teleoperation, the ASM was capable of teach/playback robotics for task execution. Details of the design, fabrication, and testing of these systems have been previously extensively in various American Nuclear Society Proceedings. Both electric servomanipulator systems performed quite well and completed many tedious tasks that current thinking claims cannot be done via teleoperation. Operators were highly skilled, technically oriented staff with thousands of hours of hands-on time. The basis for the DAWM grew out of this understanding of what could and could not be done with teleoperation and expanded into plans for added task automation with teleoperation as the baseline. The DAWM manipulators were hydraulic because that is what was commercially available and because high lift was required to support D&D. Testing culminated with a series of demonstrations at the end of fiscal year (FY) 1995.

For FY 1996, the RTDP was directed to support FY 1997 dismantlement of the CP-5 reactor at Argonne National Laboratory (ANL). Support of CP-5 required changing the focus of the dual arm technology from that of a development test bed to a system for a specific end user. ORNL teamed with the Idaho National Environmental Engineering Laboratory (INEEL), Sandia National Laboratoy, and the Savannah River Technology Center to deliver a crane-deployed subset of the DAWM, designated the dual arm work platform (DAWP), and to provide remote tooling. RTDP staff provided technical support to CP-5 for one fiscal year while Argonne staff completed all hands-on work with locally trained operators. None of the Argonne operators had previously been involved in remote systems work, and all regular operators were union employees. Argonne staff continued operation through FY 1998 and completed the remote dismantlement of the reactor internals. At that point, demolition of the concrete bioshield was to be turned over to an outside contractor. Lessons learned from this interaction were extensive.

Other than cataloging lessons learned, there were no RTDP dual arm manipulation activities for FY 1998. For FY 1999, design, fabrication, and testing of a compact remote console (CRC) for diverse remote systems was initiated. The CRC works to minimize cost, facility impact, and setup time while maintaining most of the functionality and controls capability of the DAWP operator control station as deployed at CP-5. The CRC will be used to support operation of single and dual arm manipulator systems as well as commercially available remote vehicles. Ergonomics in the context of long-term sustained operation is a major concern in contrast to systems that control cost by using suitcase or desktop controllers. In addition, collaborations with the University of Tennessee at Knoxville (UTK), Carnegie-Mellon University, and the University of Texas at Austin, which are all previous RTDP D&D development team participants, are being explored to provide true interactive telerobotic capability for any teleoperated manipulator system.

Initial DAWM Development

The original DAWM, shown in Figure 1, was based on two Schilling Titan II hydraulic manipulators mounted to a 5-degree-of-freedom (DOF) base fabricated by RedZone Robotics, Inc. All actuation was hydraulic. The 5-DOF articulation provided center torso rotation, linear actuation to change the separation between the arms, and arm base rotation joints to provide individual "elbows up," elbows down," or "elbows out" orientation for each arm. The modular package was mounted to the bottom of a rigid boom overhead transporter, and a series of tests were conducted on operations, remote tooling, and task space scene analysis (TSSA)-driven robotics. DAWM was removed from the transporter, and a crane deployment mode was also tested. A concept was developed for DAWM deployment from a large remote work vehicle built by RedZone and named Rosie; however, the program was redirected before work could begin. The various deployment modes, both completed and planned, are shown in Figure 2.

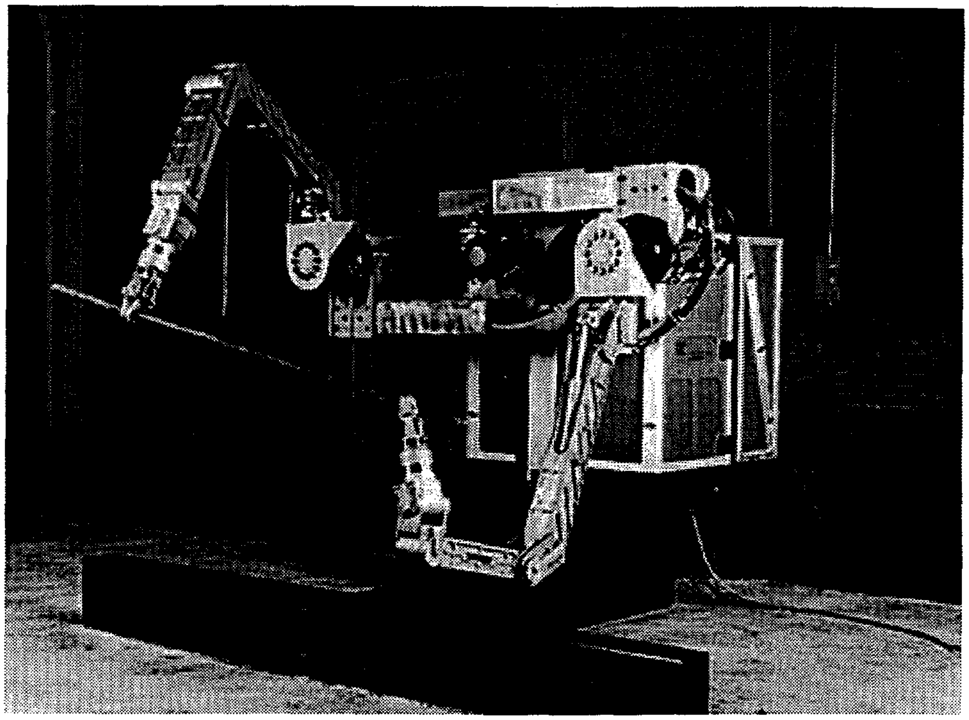

Fig. 1. Dual Arm Work Module with 5 DOF base.

The control architecture for DAWM was based on Unix development systems and operator interfaces and VME backplane-based multiprocessor VxWorks targets. In the case of the initial DAWM controller, there were five single-board computers in the VME backplane with one each for asynchronous control and communications, left master, left slave, right master, and right slave. All computer processing unit boards were located in the master backplane; the slave side backplane was connected to the master via a VME-to-VME bus repeater. The slave side input/output (I/O) contained not only all digital, analog, and resolver channels but also Schilling and force/torque sensor interface cards. The force-reflecting masters for DAWM were the full-scale ASM masters, which were refurbished to support DAWM.

The real-time software was written in C++ using Wind River's VxWorks and RTI's ControlShell for the development environment. The operator interface was done in UIMX and ran on a two-monitor VME Sparc card set. The video rack from the ASM was used to provide three 19-in. views and six 9-in. views. Operator interface menu selection provided video and camera function selection as well as manipulator parameter configuration selection for both teleoperation and robotics. Extensive previous testing had shown that graphical user interface (GUI)-based control of motions was neither precise nor effective, so camera pan and tilt and lens control were joystick or switch based.

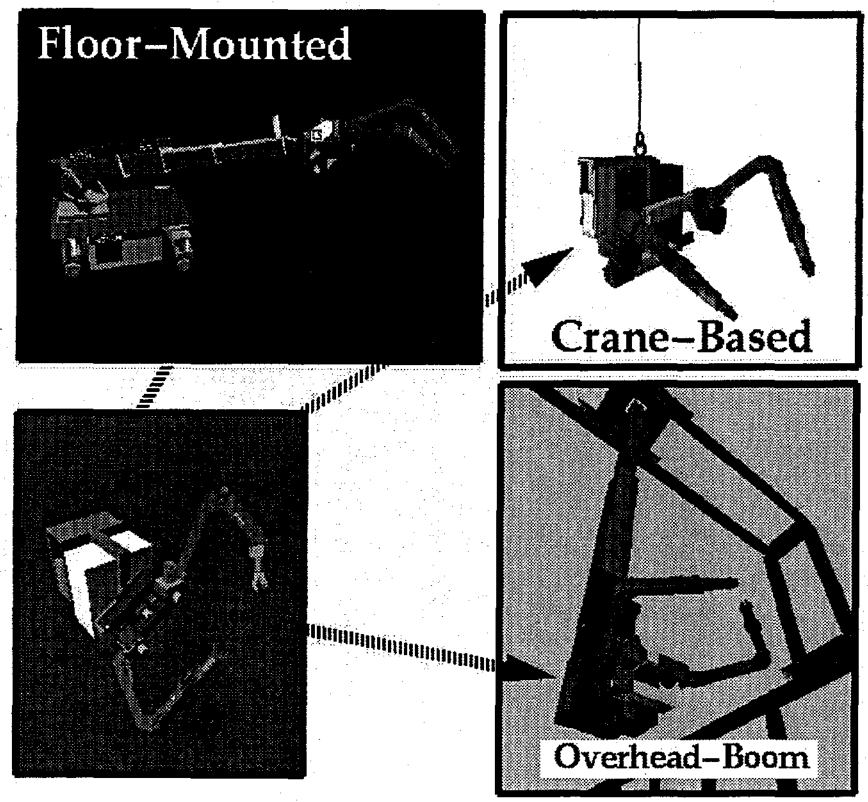

Fig. 2. DAWM deployment modes.

Because the ASM master and the Schilling manipulator were kinematically dissimilar, and because the controls were further complicated by the DAWM ability to change arm base configuration, the DAWM exclusively used a Cartesian-based control scheme. Both position and force control were implemented. Path planning and trajectory generation for robotic task execution, based on manipulator and task modeling, were managed using Deneb TGRIP on a separate Silicon Graphics workstation.

DAWP and CP-5

The CP-5 research reactor, located at ANL, was a heavy-water-moderated and-cooled, highly enriched, uranium-fueled reactor designed to supply neutrons for research. An artist's rendering, depicting a cutaway of the reactor block, is shown in Figure 3. The reactor vessel itself was 6-ft in diameter and 10-ft long. The reactor had a power rating of 5 MW and was operated for 25 years until its final shutdown in 1979. Years of operation produced activation and contamination typical of many nuclear facilities within the Department of Energy (DOE) complex. The CP-5 remote tasks included cutting and dismantling the aluminum reactor tank, disassembling and removing the array of graphite blocks, removing boral and lead sheathing and lead bricks, and transferring these materials to a staging area for packaging. The DAWP, the DAWM derivative that was supplied to the CP-5 operations staff, removed 60,000lb of graphite blocks; 1700lb of aluminum reactor vessel, piping and support bracing; 2000lb of steel; 1400lb of lead; and 620lb of boral.

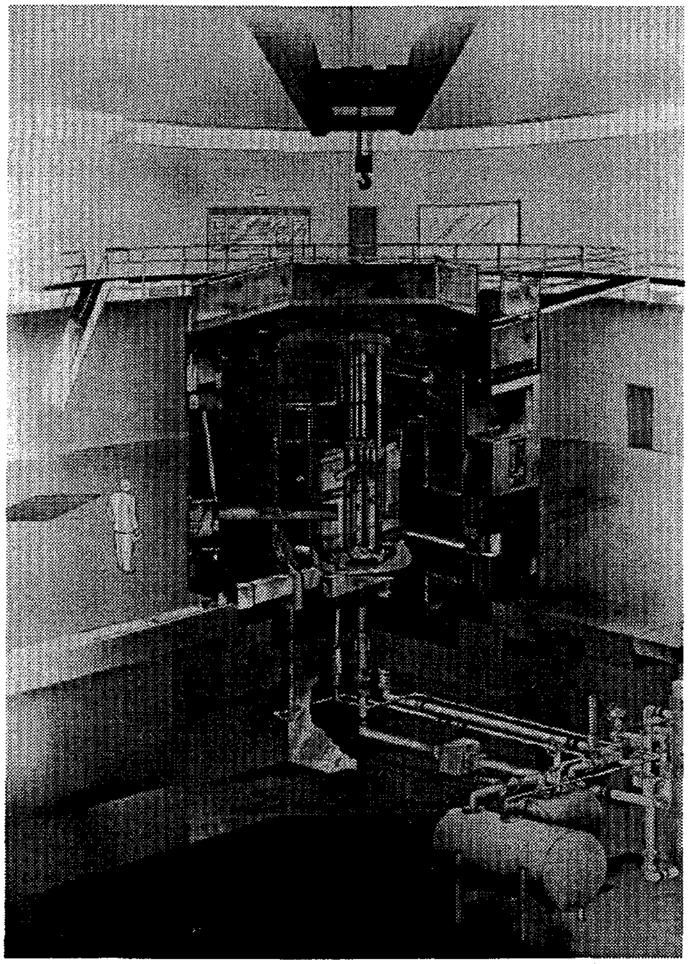

Fig. 3. Artist's rendering of the CP-5 research reactor.

Although the DAWM platform had been demonstrated as a free swinging, crane hook deployment, it was too large to fit inside the reactor block, and the kinematics of the platform were not optimum for reaching down into the reactor block with both arms at the same time. Also, the ANL requirement that existing union operators be used to operate the system dictated a change in the control system approach as well. The DAWP, shown in Figure 4, had many of the design components of the DAWM, only reconfigured for CP-5. Shilling T3 manipulators were selected because they were more easily decontaminable than the T2's. The DAWM style linear and rotary base platform actuators were also reused except that the linear actuators extended out from the base perpendicularly and the rotary joint provided a 90° change in arm base orientation from vertical to horizontal. The manipulation and base DOFs were mounted on a structure designed to be crane deployed and left either free swinging or set down on the reactor block during task execution.

Five GUI-selectable 110VAC tool ports and connections for two hydraulic tools were located on the DAWP deck. A vertical tool plate was designed for the back of the DAWP, but operations personnel chose to just stack tools on the deck for real deployment. Five pan/tilt/zoom color dome cameras were installed on the platform base to fulfill remote viewing needs. INEEL staff, who also designed and fabricated the DAWP platform and procured the T3s, provided an early version of the VirtualWindow stereo viewing system with a selectable upper and a lower camera system. Power and control to DAWP were completed via a bundled tether. Hyrdraulic supply and return were bundled separately to avoid fouling the electrical cables in the event of a leak.

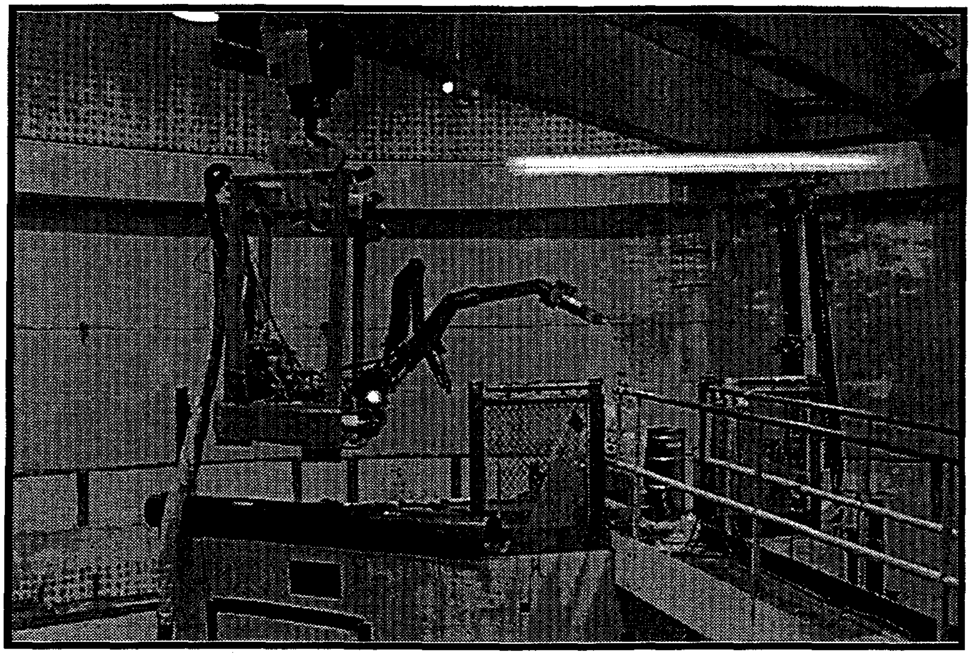

Fig. 4. Dual Arm Work Platform at CP-5.

The DAWP operator control station, shown in Figure 5, was based on the previous DAWM control station, both in configuration and in control architecture. The station was control chair-based with a separate video rack and a separate equipment rack. There were two GUI monitors, three NTSC-based video views, and one stereo view that could be switched to mono. All real-time hardware was placed in two 19-in. equipment racks, one at the operator control station and one at the hydraulic power unit (HPU) for DAWP manipulator control, which was located on the basement level under the reactor block in the containment building. Menu selections controlled which tool port was controlled by which of two foot switches, which camera view was on what monitor, and which joystick controlled which camera. Menu functions also turned the HPU on and off, selected electrical power for the cameras and manipulator controllers, and drove the platform base DOFs.

Although DAWP operations successfully completed the required disassembly of the reactor internals, lessons learned during the operation at CP-5 were extensive.[2] The lessons can be summarized into the following categories: facility support and interaction, operator skill level, hardware and software sophistication and reliability, and tooling.

Fig. 5. DAWP Operator Control Station.

CP-5 had an old control room that was made available for operator control stations for several pieces of remote equipment; however, it was not air conditioned, and the electrical power was limited. Installation of the DAWP operator station required an expansion of both power and air conditioning, which was an expense burden to the operations facility. Power consumption for the operator station should be kept to a minimum and should use only one or two 110-VAC circuits at most and a minimum of outlets if at all possible. Setting up and integrating equipment into the CP-5 facility took about two weeks. All equipment that was brought into the facility had to be moved in by ANL union staff. RTDP staff assembled equipment and made electrical connections with assistance from ANL staff. Setup time was deemed too long by ANL operations staff. The operator control station should be an integral piece to minimize setup time, as light as possible and able to negotiate normal building hallways without disassembly, and require as little and as simple separate wiring as possible.

Early on in the interaction, ANL indicated that the D&D project was to use ANL union staff already assigned to D&D the CP-5 facility to operate the DAWP. Health Physics technicians were also permitted as operators, and they were more highly educated and computer literate. None of the CP-5 staff had previous experience with remote systems or robots; however, over time several operators became proficient at operating the DAWP. All of the staff assigned to DAWP operations was expected to maintain existing work activities and multitask extensively during the workday. In contrast, remote operators at ORNL generally have an associate engineering degree and are computer literate. Since remote operation is their primary task, many have accumulated thousands of hours of operation and are highly skilled. It is unclear whether the operations environment should or even can be changed; it is more reasonable to assume that the robotics and remote systems community must conform to the education and skill level of the staff available to do the work. Operator interfaces should be simple, straightforward, and oriented towards a "hands-on" user mindset, computer-related functions should be kept more in the background and transparent to the user. Task planning, execution, and tooling should be designed to match a lower skill level than what the remote systems community normally expects.

Hardware and software sophistication and reliability were also an issue of concern. The degree of simplicity required by operations was much higher than that required by DOE development labs. The reliability expected was also higher. The DAWP computer hardware was Unix-based and was intended to stay powered at all times; this was a problem for the operations staff who expect all powered equipment to be turned on and shut down with a key switch. Facility power was also not as reliable as expected. Consequently, Unix-based hardware should not be used in future deployed systems. Battery-backed random access memory should also not be used. The controls and mechanical hardware was generally reliable. The single exception was a recurring failure of the Schilling elbow joints on both manipulators. Although the cause was never firmly established, it could have been related either to the use of HoughtoSafe water-glycol hydraulic fluid or to some peculiar stresses placed on the Schillings because of the configuration of the manipulators on the DAWP base. ORNL has since gone to use of Shell Tellus mineral-oil-based hydraulic fluid in its development systems. ANL opted to make no changes once the system was operational. Other failures included cameras and camera lenses, but these were caused almost exclusively to impact with the environment during placement of the DAWP or from the manipulators. Because this type of failure was expected, cheaper dome cameras were selected.

Tooling was consumed regularly and was both worn out and broken in operation. However, this is probably a reasonable expectation for a demolition operation. The tool that was used most during reactor vessel sectioning was a heavy-duty circular saw outfitted with a carbide-tipped blade and a vegetable-oil-based cooling system. Blades had to be changed periodically, and the saws wore out frequently. Generally, the DAWP was sent into the reactor block with several saws on its deck and did not leave until all the saws were dulled or broken. Because the saws were relatively cheap to procure locally and because they were simply outfitted with handles for remote operation and oilers for the blade, cost per saw was not severe. The general philosophy for remote tooling support for DAWP at CP-5 was to buy commercially available tools and to outfit them with handles compatible with the Schilling manipulator. Custom tooling or the use of the Schilling tool interface port was not pursued. Although control, positioning, and utilities for tooling would have been easier with the tool interface on the manipulators, the large number and wide array of tools would have made that approach too expensive. Operators did not mind the draped power cords, and even though the multiple tools on the DAWP deck did create some tangling, there were no major incidents with damaged cords. Drills, impact wrenches, cut off saws, portable band saws, air chisels, and hand tools were modified for remote operation. The only tool that showed promise but that could not be adequately deployed was a 5-hp router that was fitted with a milling bit to provide a hand-held milling machine. The target application was sectioning of the reactor vessel. The operators and the Schillings had difficulty with the large and unwieldy tool package, and it was difficult to dial in the cutting speed on the milling bit such that it would cut the aluminum vessel but would not melt the aluminum and foul the bit. Precise positioning was also difficult. This was the primary disappointment in the tooling because it showed great promise but the implementation could not be adequately worked out. In general, tooling and efficiency of operation were an issue. Highly automated tooling would have been too costly and required too much time to adapt and test for the changing CP-5 scenarios; however, using simple tooling without operator assists can be difficult for inexperienced operators. A new in-between tooling philosophy should be developed that emphasizes smarter tooling with operator assists but does not go so far as to require the costs of full automation. A development effort is needed to establish what the reasonable bounds are.

Strategy to Return to Development

While the RBX Program and the D&D Focus Area have a high priority on the deployment of technology into environmental management projects and although the deploying DAWP for CP-5 provided invaluable experience, the primary RBX focus is technology development. This section outlines the restart of work in dual arm manipulation and proposes a directed development effort, molded by lessons learned, to produce more capable and cost effective solutions for the end user.

To address the need to reduce deployment costs, setup time, and facility impact, work has been initiated on the CRC. A crude sketch of the CRC is shown in Figure 6.

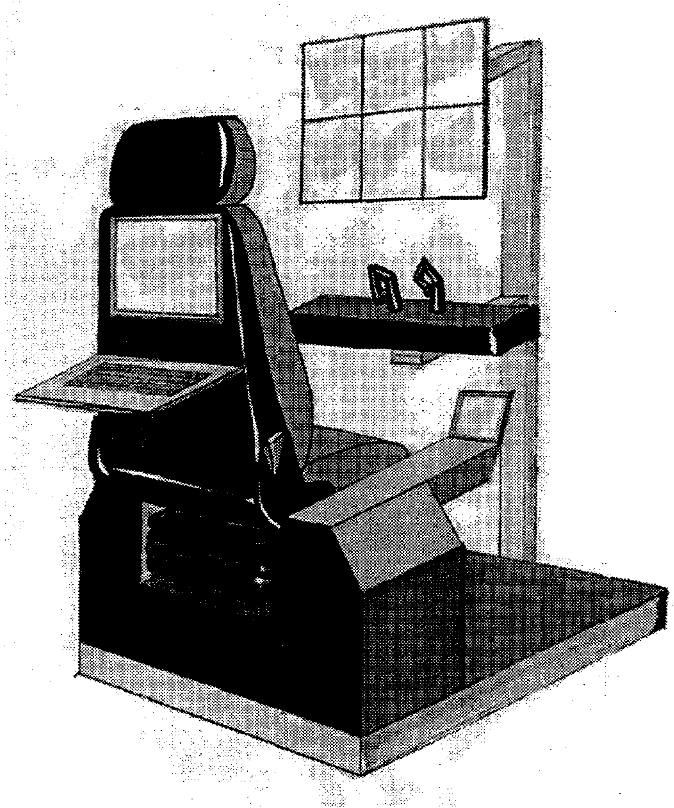

Fig. 6. Early Concept Compact Operator Console.

The basic physical features of the CRC include the following:

1. No assembly required; the CRC is shipped assembled as an integral unit. Removable panels are added to the top and sides so that the unit can be shipped without a packing crate.
2. CRC is small enough to be wheeled through normal hallways and doorways, and the operating footprint is kept to a minimum. Weight is minimized as much as practical.
3. Power consumption is minimal and will be supplied by one or two 110-VAC circuits; auxiliary cooling is not required.
4. Cost control is a primary design driver.
5. Human factor issues are not compromised so that the console can be comfortably used for extended daily operations. The baseline capability is that of the CP-5 operator control station. The central focus on the control chair remains.
6. The design is modular, permitting easy upgrades and integration of other vendor's equipment.

The basic system level features include the following:

1. The system is stand-alone and contains all development system software, backup and restore capabilities, and diagnostics internal to the control station computer hardware. Internet access is supported but is not required for any development or diagnostic functions.
2. Menus and I/O mapping are designed such that they can be readily changed as the system grows and changes with the operating environment.
3. PC-compatible hardware will be used to control costs and to make replacement parts readily available.
4. Windows NT will be the baseline operating system. Issues related to which real-time extension or operating system should be used are being examined.
5. Commercially available software packages will be used wherever possible.

The CRC is currently in the detail design phase. To save on cost of implementation by eliminating the need for video racks and cooling, flat liquid crystal displays will be used for the NTSC video provided for remote viewing. The displays will be smaller and closer to the operator, maintaining the human factors guideline that the operator to screen distance should be 2.5 times the diagonal of the view for normal NTSC resolution to maximize detail resolution while avoiding pixelation.

Head-mounted displays should continue to be reviewed periodically and should be considered the ultimate direction of remote viewing, but it is believed that they are not ready for the rigors of extended daily operations (6 to 10 hours per day). Head-mounted displays need to incorporate all auxiliary remote views (picture-in-picture capability) and all GUI functions before they can be used practically. Although, head tracking and voice recognition should be pursued and should be expected to be part of the operator interface of the future but should be highly reliable before implementation; they will not be part of the CRC initially.

The CRC will put all operator interface control hardware in a box that is in the base of the control chair. Technology associated with the current trend in wearable computing should be implemented to minimize size and power consumption. Someday, this may also permit wearable operator interfaces. Extensive testing during the last two decades has continually shown that some functions are better performed by manual controls (joysticks, levers, switches, etc.) and that some are suitable for GUI implementation. Side consoles will be mounted to the chair that will permit access to touch screens for menu selections and physical inputs, such as joysticks, for manual control of moving equipment. Foot switches have been shown to be excellent for controlling auxiliary functions such as tooling; two foot switches will be provided in the CRC.

Besides the need to reduce the cost and facility impact and to increase the user friendliness of using robotics and remote systems technology, the capability to improve the "production rates" of operation needs to improve significantly. This is best described in the context of the DOE applications; the following systems need to be addressed.

The first aspect requires a return to a focus on implementation of true telerobotics in remote manipulation, whereby a quality teleoperation system is also capable of significant automation. In the case of CP-5, operator assists in holding a saw in a specific plane or around a certain radius at a specified cutting rate would have reduced reactor vessel dismantlement time. Such tasks typically resemble machining operations rather than articulation of objects. UTK is currently pursuing work in this area that is applicable to a next-generation DAWM. Designing an operator interface in a context for the typical operator's use will be a particular challenge. UTK is also pursuing a much higher level of automation with furtherance of the previous ORNL/UTK TSAA work. This system will provide operator-assisted vision-based identification of objects and tasks specified to operate on those objects, such as specifying a certain pipe, locations where to cut that pipe, and then guiding the cutting action. Again, an operator interface that the typical operator can make use of will be critical.

Also for CP-5, much higher gripper dexterity would have minimized tool modification, allowed the use of larger tools with both "hands," allowed the use of smaller tools for delicate tasks and the ability to more readily pick up smaller objects, and maximized tool articulation for the job at hand. At CP-5, it was common to have very delicate tasks and high lift tasks in the same sequence of operations. This will be true of almost any hardware system not specifically designed for remote maintenance. Removing small allen-head cap screws and changing a blade in a saw are examples of tasks that fit the high-dexterity level necessary. Such needs will require development of alternative grippers or "hands" to meet the high-dexterity requirements while still meeting the robustness of the standard two-finger gripper. No known work is in progress that meets both criteria.

These same criteria would also directly apply to the serious need for robotic and remote systems in the case of in situ dismantlement of the glove boxes in Building 776 at Rocky Flats. In this case, there is also a need for a serious improvement in robotic/remote system mobility because this facility was designed for human access only; doorways, hallways, and spacing between and around equipment to be dismantled is very restricted. Typical large systems could not be implemented without modifying the building or dismantling and moving equipment for each glove box disassembly, which will expose workers to the risks that use of the remote systems are trying to prevent initially. This particular example will require deployment of a mobile platform that requires no more spacethan a human and that is capable of readily negotiating typical factory floor obstacles. A small footprint tracked vehicle might be considered acceptable for many applications until ladders are considered. Many of the Building 776 activities will have to be conducted as much as 15 ft from the ground, with an array of process piping and building structures blocking the way overhead. Although there are currently an array of vehicles in either concept or hardware available, none seem to address these particular requirements. To date, most remote systems have required a custom deployment system designed for a particular task; development of a more generic high-mobility package would help alleviate implementation costs.

Automation will help to significantly reduce task completion time, but teleoperation will continue to be the predominant baseline for the foreseeable future. In order to address the needs of DOE's site remediation, the quality of teleoperated systems needs to improve significantly. High-quality telepresence is at the core of the dexterity and mobility issues mentioned previously, and these systems need to be easy to use by cleanup staff with minimal education and training. It appears that the more anthropomorphic the interfaces to remote viewing and the manipulation are, the better an operator will be able to execute tasks in a reasonable time from an operations perspective.

Summary

This paper presents and reviews a history of RTDP/RBX dual arm manipulation work in the context of what development work should continue to best serve DOE's needs. The path forward should include the pursuit of high-quality telepresence, focusing on high-dexterity and remote viewing that provide the operator with an anthropomorphic viewing and manipulation capability for the most efficient task completion and minimum training time. In addition to high-fidelity telepresence, full telerobotics needs to be implemented to provide operator assists above and beyond normal manipulation to serve the frequent machining-type tasks. As practical and possible, higher levels of intelligent automation, such as TSSA-driven robotics, should be added.

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