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REMOTE DISMANTLEMENT TASKS FOR THE CP5 REACTOR: IMPLEMENTATION, OPERATIONS, AND LESSONS LEARNED*

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REMOTE DISMANTLEMENT TASKS FOR THE CP5 REACTOR: IMPLEMENTATION, OPERATION, AND LESSONS LEARNED*

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ABSTRACT

This paper presents a developer's perspective on lessons learned from one example of the integration of new prototype technology into a traditional operations environment. The dual arm work module was developed by the Robotics Technology Development Program as a research and development activity to examine manipulator controller modes and deployment options. It was later reconfigured for the dismantlement of the Argonne National Laboratory Chicago Pile #5 reactor vessel as the crane-deployed dual arm work platform. Development staff worked along side operations staff during a significant part of the deployment to provide training, maintenance, and tooling support. Operations staff completed all actual remote dismantlement tasks. At the end of available development support funding, the Dual Arm Work Platform was turned over to the operations staff, who is still using it to complete their dismantlement tasks.

I. BACKGROUND

The Robotics Technology Development Program (RTDP) of the Department of Energy (DOE) is a multi-national laboratory program that has been involved in developing various robotics and remote systems technologies to meet the environmental restoration needs of the DOE national laboratories. One of the many development focus areas is decontamination and decommissioning (D&D). While many of the D&D dismantlement and clean-up tasks can and will be handled manually, remote completion of D&D efforts is desirable to limit human exposure where radiation and contamination levels are high. Regulatory direction has also been forcing a decrease in the level of exposure that is considered acceptable to a level that is "as low as reasonably achievable" (ALARA). Tasks that have been performed by suited humans in the past will eventually have to be performed remotely. The dual arm work module (DAWM) was developed to study manipulator configurations, control modes, and deployment options for heavy-lift hydraulic arms such as would be necessary for the larger scale remote dismantlement tasks.

II. DAWM

The original DAWM consisted of two 6-degree-of-freedom (DOF) Schilling Titan II hydraulic manipulators mounted to a 5-DOF hydraulic positioning base that was designed and built to specification for Oak Ridge National Laboratory (ORNL) by RedZone Robotics, Inc. (Fig. 1).

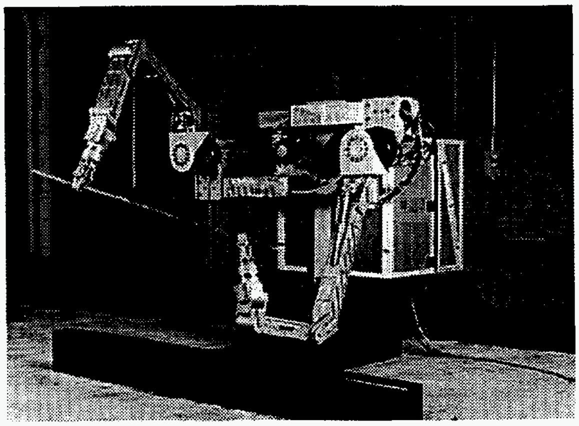

Fig. 1. Dual Arm Work Module.

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The DAWM base motions provided for a seventh DOF at the base of each Titan II so that manipulation could be approached from an elbows-up, elbows-out, or elbows-down configuration, depending on the task at hand. Past testing had shown that an elbows-up configuration was advantageous for operation from above on horizontally configured equipment. An elbows-down configuration was advantageous for working on vertically stacked equipment. The elbows-out positions allowed the manipulators to reach around obstacles, if required. Two linear actuators were used to vary the base of the arms anywhere between a separation of 60 to 150 cm. A center rotary actuator provided ±90° rotation of the entire torso from the horizontal position maximizing flexibility of the DAWM manipulation capabilities. The DAWM package was mounted to a rigid boom overhead transporter, but a major emphasis was placed on examining a whole array of deployment options to cover the needs of various facilities. Besides overhead transporters, overhead crane- and floor-based vehicle deployment were also accommodated in the initial design (Fig. 2).

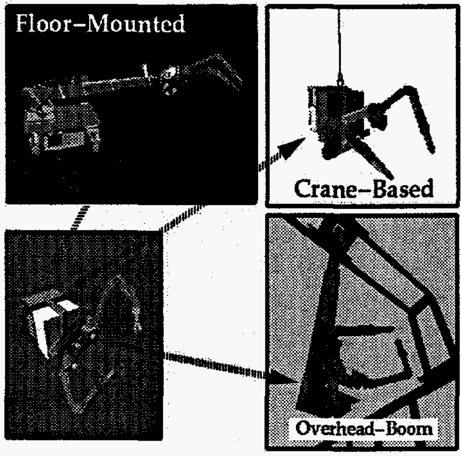

Fig. 2. Multiple DAWM Deployments.

The Schilling hydraulic manipulators provided higher lift capacity than that normally available for dexterous teleoperators with 110 kg in the elbows-up configuration, 70 kg in the elbows-out configuration, and 80 kg in the elbows-down configuration, all at the maximum extended reach of 190 cm. The master controller for the DAWM used converted hardware from the advanced servomanipulator (ASM), a manipulator designed and extensively tested at ORNL in the 1980s. The ASM was a fixed configuration, elbows-down, remotely maintainable manipulator that was designed to meet the needs of high radiation facilities. The full-scale master controller was force reflecting. Robotic operation and teleoperation of the DAWM manipulators were handled in a Cartesian rather than a joint level mode. Cartesian control was chosen since it had several advantages from a development perspective. For both robotic and teleoperation mode, the manipulator controller software was kept the same. Only the front end changed as to whether the master controller or trajectory planner was driving the manipulator end effector. The graphical user interface was unix-based, and the real-time control hardware was VME-based, using five single board computers located in a master rack in the control room and connected to a slave rack on DAWM through 90 m of fiber optic cables.

Testing was completed in 1995-1996 on various teleoperator controller modes and tools, and several demos were conducted for transporter- and crane-based deployment as well as a task space scene analysis driven robotics automation capability.

III. ARGONNE NATIONAL LABORATORY CP-5 RESEARCH REACTOR

The Chicago Pile #5 (CP-5) reactor (Fig. 3) was built as a heterogeneous, heavy water cooled and moderated reactor to provide neutrons for research at Argonne National Laboratory (ANL). Construction of the reactor facility was started in 1951; operation began in 1954; and shutdown of all operation occurred in 1979. As part of the final shutdown process, the reactor was defueled and drained of heavy water. System piping, auxiliary systems, and miscellaneous hardware were removed and packaged as waste in order to put the facility in a safe storage mode. D&D of the reactor started in 1995. Throughout the D&D process, a number of new and innovative technologies from various government and industry groups were to be demonstrated and evaluated for future use. In 1996, the RTDP D&D robotics team was directed to provide robotics and remote systems support for the dismantlement of the CP-5 reactor internals beginning in 1997.

IV. DAWM TO DAWP EVOLUTION

It is important to note that the original DAWM design was driven by the desire to provide maximum system control and configuration versatility for the study of deployment options and orientation relative to specific task performance. CP-5 support requirements were completely different. The only reasonable deployment method was via suspension from the facility's overhead polar crane. Size constraints were an issue since the reworked dual arm manipulator system had to fit inside the 3-m steel cylinder that separated the reactor internals from the biological shield. DAWM was designed more to maximize manipulator reach rather than to minimize system footprint.

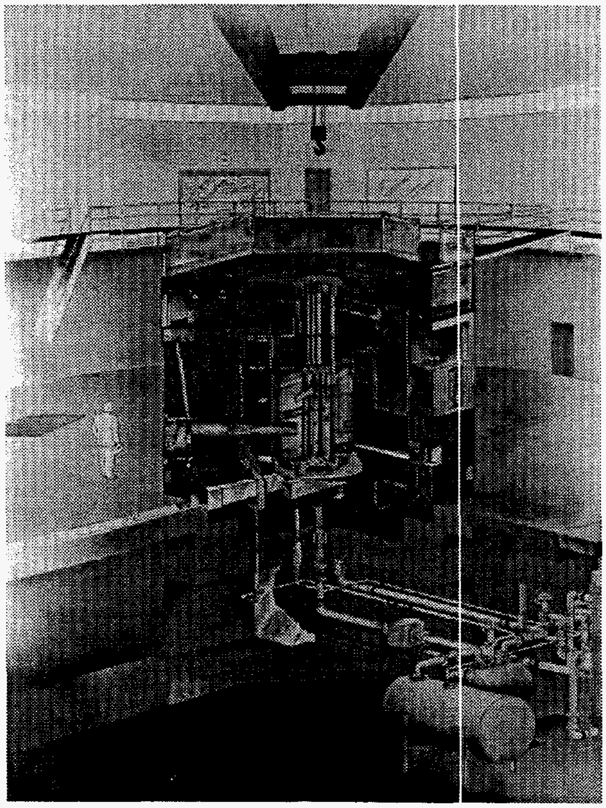

Fig. 3. CP-5 Artist's Rendering.

A study of the tasks and constraints involved and the available deployment options led to a subset of DAWM designated the dual arm work platform (DAWP) (Fig. 4) by RTDP team members at the Idaho National Environmental Engineering Laboratory. DAWP was specifically designed around crane hook deployment, and the base DOFs were reduced to four instead of five and reconfigured to accommodate each requirement in the restricted footprint. The base actuator kinematics were chosen such that the manipulator envelope was maximized to reach out, across, and down into the reactor vessel when the DAWP was placed on top and to the side of the reactor. DAWP made use of the existing DAWM base platform hydraulic actuator components in the redesign. Schilling manipulators were also used; however Titan III's instead of Titan II's were installed since they were specifically designed to be more decontaminable. The operator control station (Fig. 5), very closely patterned after that of the DAWM, was provided by ORNL. The hardware control architecture for the DAWM and a significant portion of the DAWM control system were used on DAWP. The most notable difference between the control schemes of the two systems was the use of Schilling mini-master controllers on DAWP instead of DAWM's full-scale force reflecting master controllers. This decision was driven totally by cost and did impact performance. While all of the DAWM-VME based control hardware was left intact for DAWP, use of the Schilling mini-masters was not conducive to the DAWM Cartesian controller scheme, and the Schilling proprietary controller boxes were installed in addition to the VME controller and used as the baseline controller mode with the VME hardware on hand for advanced control capability as time permitted. Five color cameras provided remote viewing with pan, tilt, and zoom capability selected. They were not radiation hardened but were environmentally sealed via a Plexiglas dome over the camera package. B&W single-board cameras were packaged in low profile enclosures and used on each manipulator wrist. Two pairs of stereo cameras, the INEEL VirtualwindoW system, were also available for operator use.

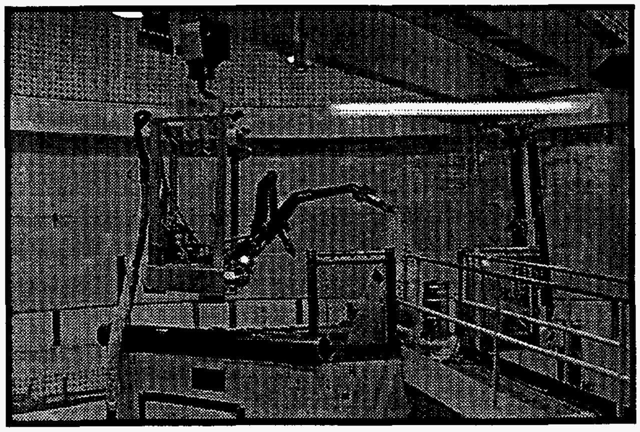

Fig. 4. Dual Arm Work Platform.

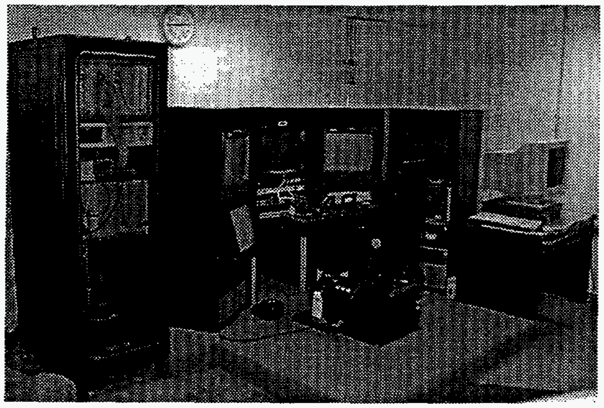

Fig. 5. DAWP Operator Console.

V. INSTALLATION AND START-UP

CP-5 had allocated control room space for the DAWP operator interface and master controller rack, but the power and air conditioning requirements made it necessary for them to make facility modifications. The DAWP slave rack hardware and hydraulic power unit were installed in the basement, one floor down from the reactor shell floor, and the 30-m tether bundle containing electrical and hydraulic lines from the slave rack to the DAWP were routed through the floor to the shell above. DAWP was placed in a maintenance stand on the floor outside the reactor's biological shield in the reactor shell. The whole early stage of operation permitted limited human access to the shell floor for operational support and DAWP maintenance as needed. After installation and debugging of the DAWP hardware, a significant training period began. ANL had specified that ANL operations staff completes all remote operations; however, at the initiation of this effort, they had no trained remote operators. A training course was developed and operators were trained on DAWP using simple mock-ups in the first quarter of 1997. ORNL first trained ANL engineers, whom then conducted operator training.

VI. TASKS AND TOOLING

The specific tasks expected for the DAWP included installing and hooking up lifting fixtures for the heavy components that must be removed intact such as shield plugs; unbolting, shearing, or sawing miscellaneous internal support hardware; removal of thousands of graphite blocks; sectioning the aluminum reactor vessel; and assisting with waste packaging and disposition as practical (in this mode, DAWP was placed in a stand on the reactor room floor). DAWP was designed to carry and deploy up to seven tools at a time, five electric and two hydraulic, to assist in completing the various tasks. The tool philosophy, as dictated a priori by the program, relied on the use of portable power tools fixtured with Schilling T-handle brackets so that tooling costs could be minimized and so that changes in plans and methods of removal could be rapidly accommodated. Schedule and cost issues prevented any significant use of mock-ups to develop and verify tooling.

ORNL provided an initial set of tools: impact wrenches, a powered right-angle drive, side grinders with cut-off wheels, reciprocating saws, circular saws, a router-based milling head, and drills. As time went on, ANL became more involved in tool selection and modification for remote use, including hand-held bandsaws, heavy-duty circular saws, and impact chisels. Cutting tools used vegetable oil-based lubrication systems to extend blade life. No flame-based cutting was allowed, and the use of pneumatics was discouraged because of concerns over spread of contamination.

The early "hot" tasks were actually tasks that could have been conducted manually because of relatively low activation level but were done with the DAWP to gain operator experience and to avoid needlessly accruing worker exposure against the permitted worker dose budget. For these tasks, DAWP was left on the reactor room floor in its maintenance stand, and the task items were flown down to the DAWP from the top of the reactor. These tasks included sectioning and packaging a vertical rod assembly (Fig. 6) and sampling (by drilling) stainless steel plug sheathing to determine activation levels. While the vast majority of the other tasks were completed with DAWP suspended from the overhead crane and on top of or in the reactor, these early tasks did set a precedent, and it was not unusual for operations staff to choose to fly a task down from the top of the reactor in order to have more space available to complete a given task.

The next sequence of tasks involved removing the shield plugs from the top of the reactor. Since the plugs provided adequate biological shielding, almost all of this work was done manually and so will not be discussed further. However, DAWP was used to cut out sections of a flexible coupling and to remove the bolts that held in the flanges of that coupling; this was necessary in order to release one of the shield plugs from the rest of the structure.

Once the plugs were pulled, DAWP's main task was to section the aluminum reactor vessel, which was 1 cm thick, and to remove all interior graphite blocks working from the top of the reactor down. The reactor vessel also contained various size horizontal thimbles for experiment insertion as well as structural pieces of aluminum. The best tool for the task proved to be a heavy-duty circular saw. Frequent blade changes were required, so several saws were plugged into DAWP at one time when all the blades were worn out, DAWP was flown from the top of the reactor to the stand, and all saws were serviced. After removing the first top 60 cm intact, further progress was best achieved by chiseling out and removing graphite blocks to clear the way for the DAWP manipulators to use the circular saws to make outside cuts on the vessel. By this time, CP-5 operations staff was completely on their own with no RTDP staff on site to support operation and maintenance.

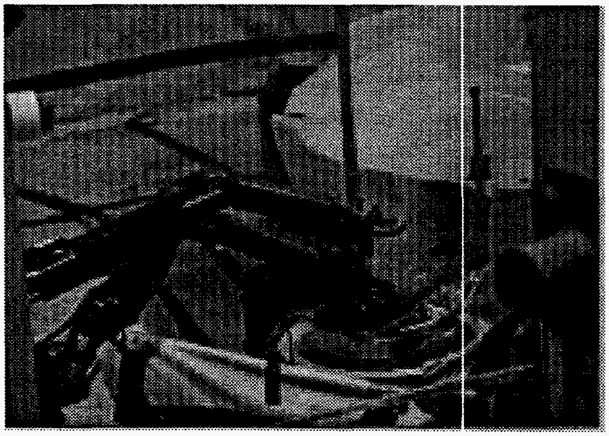

Fig. 6. DAWP uses a "hand-held" bandsaw.

VII. LESSONS LEARNED FOR DEVELOPMENT STAFF

The basic DAWM controls architecture was chosen and designed to have extensive capability to support research activities; however, this required a high degree of hardware and software complexity that is not conducive to the operations environment. Operators were frequently overwhelmed by too many choices in the controllers, remote viewing, tooling, etc., and the level of computer literacy was radically different from that of the research staff. While this was expected and while an attempt was made to compensate for this difference in the initial design, the typical operator still had difficulty adapting. Controls should be simplified further and operator choices limited. Standard industrial control interface hardware and PC-based controllers should be used for fielded systems wherever possible, for the sake of maintenance familiarity and ready availability of replacement parts.

The DAWP operator interface, control, and platform hardware were generally very reliable. Most of the sensor, camera, cabling, and actuator problems on the DAWP base were related to impacts due to environment, tools, and manipulators. D&D activities were generally rough on the hardware. In general, development staff tended to be too worried about keeping all of hardware working perfectly. Operations staff quickly learned to focus on the task at hand and only dealt with damaged hardware when enough items were broken to finally prevent task completion.

Tether management was a significant and constant concern during operations, especially since the DAWP was frequently moved from the floor to the top of the reactor. An on-board hydraulic power unit would have greatly simplified and decreased the size of the tether bundle but would have increased the size, weight, heat dissipation, and maintenance burden on the DAWP. Difficulty with tether management was one of the operations complaints about the DAWP design.

Early on in DAWM development, Tennessee environmental regulators requested that water-glycol hydraulic fluid be used instead of standard hydraulic oil. As a result, water-glycol was used in the DAWP system as well. This caused problems with the Schilling manipulators since the fluid is conductive and caused corrosion in the electrical cabling and connectors used for the servovalves and sensors. Any hydraulic leaks caused maintenance problems, both with required cleaning up the hydraulics and with shorting out of the electric. Mineral oil (such as Shell Tellus) should be used wherever possible, as it causes none of these problems.

Physical size, electrical power, and cooling requirements of the DAWP operator interface proved to be a burden to the CP-5 facility. While operations staff would consider this an obvious issue, power requirements should be kept as low as possible, requiring only a couple of standard 110VAC outlets, and hardware should be designed such that no cooling other than fans are required over a wide range of operating temperatures. While the development team provided the CP-5 DAWP operator control station, frequent questions about replication costs for duplicate systems revealed that the use of unix- and VME-based computers is too expensive for the current level of operating budgets. However a change to a Windows NT PC-based approach would have to tolerate more system crashes and slightly decrease system performance in exchange for the lower cost.

The tooling and mock-up philosophy also revealed some interesting issues. While the use of the Schilling T-handle to interface tools to the manipulator provided a fast and cheap way to adapt standard power tools for remote use, it did not permit the solid connection to the end of the manipulator and elimination of cabling that removable grippers and tool connector interfaces permit. However, the quantity and variety of tools used by DAWP would have made purchase of those tool connectors prohibitively expensive and would have made fast adaptation of new tools difficult. The answer to this problem is somewhere in between the two approaches with more attention being given to tool guides, fixturing, and even tool automation, if appropriate, but without going to the full tool interface on the manipulator.

VIII. SUMMARY

The migration of hardware from the development laboratory prototype to the fielded system was successful in the case of the DAWM/DAWP transition. However an extensive and long-term interaction between the development staff and CP-5 operations staff was necessary in order to insert the technology into the real world and to allow operations staff to acclimatize to the system. Future designs can improve their probability of success and reduce their transition time by addressing the concerns outlined in this paper.

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