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Mobile Workstation for Decontamination and Decommissioning Operations

Topical Report

**W. L. Whittaker
J. F. Osborn
B. R. Thompson**

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Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia**

By

**The Robotics Institute
School of Computer Science
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, Pennsylvania 15213**

and

**RedZone Robotics, Inc.
2425 Liberty Avenue
Pittsburgh, Pennsylvania 15222**

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Abstract

This project is an interdisciplinary effort to develop effective mobile worksystems for decontamination and decommissioning (D&D) of facilities within the DOE Nuclear Weapons Complex. These mobile worksystems will be configured to operate within the environmental and logistical constraints of such facilities and to perform a number of work tasks. Our program is designed to produce a mobile worksystem with capabilities and features that are matched to the particular needs of D&D work by evolving the design through a series of technological developments, performance tests and evaluations.

The project has three phases. In this the first phase, an existing teleoperated worksystem, the Remote Work Vehicle (developed for use in the Three Mile Island Unit 2 Reactor Building basement), was enhanced for telerobotic performance of several D&D operations. Its ability to perform these operations was then assessed through a series of tests in a mockup facility that contained generic structures and equipment similar to those that D&D work machines will encounter in DOE facilities. Building upon the knowledge gained through those tests and evaluations, a next generation mobile worksystem, the RWV II, and a more advanced controller will be designed, integrated and tested in the second phase, which is scheduled for completion in January, 1995. The third phase of the project will involve testing of the RWV II in the real DOE facility.

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1. Executive Summary

1.1 Program

Carnegie Mellon University and RedZone Robotics, Inc., have undertaken a multi-phase effort to develop mobile worksystems that can perform decontamination and decommissioning (D&D) operations. It is a program of research, development, demonstration, testing and evaluation activities whose objective is to create technology and an associated experience base upon which robotic D&D operations can be grounded. The project stems from an earlier association with the related problem of nuclear accident recovery in which a teleoperated mobile worksystem, the Remote Work Vehicle (RWV), was developed for use in the Three Mile Island Unit 2 Reactor Building Basement (TMI-2 RBB). Though successfully demonstrated at TMI, the RWV was never deployed and was ultimately returned to Carnegie Mellon. Using the existing hardware as a basis, we have enhanced its capabilities and tailored the worksystem more for the needs of DOE facilities. Through enhancements and upgrades of the original RWV and its control console we have overcome several of its deficiencies, creating an advanced testbed for D&D work.

The program is divided into three phases, each at a higher level of maturity, and will culminate with the commercial availability of mobile worksystems matched to the needs of facilities within the DOE's Nuclear Weapons Complex. Phase 1, which is described herein, produced an advanced testbed which executed representative tasks in mockup situations. Further, the system was evaluated to ascertain its suitability for decontamination and decommissioning. This information, in conjunction with an analysis of the worksystem's ability to withstand the expected rigors in real settings, will be used to develop a high performance prototype, RWV II, in Phase 2.

In Phase 3, RWV II will be tested and evaluated in a mockup of a selected DOE facility and then demonstrated in the real facility. We have identified two potential scenarios for demonstration of the RWV. One is the Integrated Process Demonstration Facility (IPDF) at Oak Ridge National Lab. The IPDF is designed for reprocessing spent fuel rods and has many features representative of other DOE facilities including interconnected pipes, pumps, tanks and process equipment and support structures. Another opportunity is decommissioning of a small research reactor facility in Saxton, PA, that is owned by General Public Utilities, Inc. (who also operates Three Mile Island). Both facilities have relatively low levels of contamination with only a few isolated alpha and beta sources and can currently be entered by human workers without protective clothing, thus, making them advantageous for first experiences in real operations.

1.2 Worksystem Description

The RWV testbed is a telerobotic, electrohydraulically powered mobile worksystem equipped with tooling to perform D&D tasks, including decontaminating and sealing concrete and steel structures and surfaces, dismantling equipment, cutting pipes, packaging and transporting materials, acquiring data for radiological and contaminant mapping, and performing general inspections. The need to productively and cost effectively perform such tasks in DOE facilities drove the upgrades to and reconfiguration of the original, purely teleoperated RWV. These upgrades included installation of a new on-board real time computer control system to coordinate robot motions and monitor status, development of a new off-board console to operate the robot and observe task execution, and development of a new suite of tools.

The RWV worksystem is based on a four-wheel drive locomotor with computer coordinated four-wheel steering designed for omni-directional driving on flat floors. The locomotor supports a tilting, telescoping boom to which a tilting tooling platform is appended; all three axes of boom motion can be run individually or coordinated to control tool position and orientation. Riding atop the tooling platform is a six degree-of-freedom electrohydraulic master/slave servo manipulator with a 55 lb payload for dexterous work with light tools and end effectors including a grinder, a sprayer, a crow bar and a parallel jaw gripper. A two degree-of-freedom electrohydraulic tool deployment mechanism is mounted beneath the tooling platform to position heavier tools such as a hydraulic shears and a reciprocating saw. Other on-board RWV subsystems include a hydraulic supply and distribution system, a seven camera video system, a tether management system, an electrical power distribution system, and a variety of status sensors.

The RWV is controlled from a single-operator control station that houses joysticks for locomotor and boom control, a master arm to control the manipulator, video and audio monitors, and a three-dimensional graphical display of the robot configuration. The console is connected to the robot through an intermediate Power Distribution Unit (PDU); a multi-conductor tether between the RWV and the PDU provides for power and signal transmission.

1.3 Worksystem Testing

Testing in the first phase of the program was designed to produce *qualitative* data on the quality of control system and operator interface designs. We constructed a testing facility that is representative of DOE facilities in which mobile worksystems will operate in the future. The workspace is an industrial setting that contains structures, equipment, piping, valving, and ductwork found in processing and assembly plants. The mockup was designed to be easily reconfigured to test driving and manipulation in several operating scenarios and to allow safe operation of the robot.

Using DOE documents that describe general needs for D&D throughout the nuclear weapons complex and particular site requirements and priorities, we developed hypothetical scenarios in which mobile worksystems might operate. We then analyzed the tasks to be performed remotely to devise a series of tests of the RWV's capabilities.

For each test we created a written task description detailing the operation(s) to be performed, a photograph and/or schematic representation of the test site configuration and a list of task constraints. Following each task the operators were asked to assess difficulties in executing the task and appropriateness of the tools used, to list strengths and weaknesses of the worksystem control console and controller, and to make recommendations for improving efficiency and effectiveness.

After all the tests were performed, we examined the logs to determine which factors most strongly affected performance. The test data allowed us to analyze which features of the worksystem, controller, and console were most useful, which were least useful and what improvements were warranted.

In addition to the evaluation forms, each test was documented in several other ways. Extensive use was made of videotaping to record worksystem actions in the mockup, operator actions at the

console, and teleoperation camera views. In most tests, the "bird's eye" camera view was recorded on a VCR in the console; a tripod-mounted camcorder in the work area was used in some tests. Throughout the testing program, all maintenance performed on the worksystem, console and controller was noted in a log book.

1.4 Results

After executing the tests, we examined the evaluation forms to note what factors most strongly affected performance of the worksystem and the ability of the operators to complete the assigned task. A summary of these results is presented below.

- Driving is a necessary aspect of every task performed and accounts for a significant fraction of the overall task execution time. Remote driving is generally more difficult than remote manipulation.
- The RWV has mobility characteristics that are well-suited for driving in flat floor environments.
- The RWV has appropriate manipulator kinematics and sufficient dexterity for many classes of D&D tasks. Operation of many tools requires dexterity and precise manipulator control.
- Separating manipulator control from the rest of the robot (locomotion and boom functions) allows straightforward control of end effectors.
- Control of manipulator position is sufficient for some, but not all D&D tasks. Different modes of manipulator control (e.g., force control) are better suited for some tooling operations.
- Many shelf-available tools can be readily adapted for remote performance of D&D tasks. Hydraulic tools are preferred over electric tools. A heavy tool positioning mechanism allows the use of tools too heavy for the manipulator.
- The ability to deploy multiple tools and remotely interchange them facilitates many D&D tasks.
- Good ergonomics are essential for effective operator interfaces. The RWV console is well designed for single-operator telerobotic control.
- Better feedback to the operator can improve both remote driving and remote manipulation.
- Operator skill level and experience significantly affects overall performance and efficiency of remote work.
- The RWV's scale, hydraulic actuation of primary motions, and real time processing system are appropriate for D&D operations.
- Good documentation is essential for maintenance, debugging, and worksystem upgrades.

1.5 Future Work

In Phase 2 of the project, we will conceive, design, build and test a next generation mobile worksystem, the RWV II. This system will be designed using knowledge gained in Phase 1 about DOE's programmatic approach to environmental restoration and waste management as well as conclusions drawn from the testing of the RWV testbed in Phase 1. Our primary objectives for Phase 2 are:

- produce a modular robotic system able to perform D&D tasks in real operating scenarios within the DOE complex;
- enhance mobile worksystem effectiveness and productivity through improved operator interfaces and telerobotic control;
- incorporate and complement technologies developed in other ER&WM programs; and
- improve the knowledge base for performing decontamination and decommissioning operations with telerobotic systems.

A significant distinction between RWV I and RWV II is that the latter will be designed for greater modularity to facilitate interchange of power sources, tooling deployment platforms, manipulators, tools and sensors, allowing a wider range of tasks, facilities, and problems to be addressed. The locomotor, tooling platform and tooling will be self-contained by virtue of local actuation, local sensing and local controllers, allowing subsystems to be readily interchanged. An important aspect of this design approach is that it will create opportunities to adapt technologies under development in other ER&WM programs for use with RWV II.

In addition, we will integrate sensing capabilities to build a 3D workspace model to improve the operator's understanding of the work environment. We intend to adopt the *Generic Intelligent System Controller* (GISC) paradigm as the means to organize and refine the RWV software architecture developed in Phase 1. The essential element of GISC is the Workspace Modeler, a module that maintains a representation of robot state and state of the world around it. The Workspace Modeler embodies *a priori* information including robot geometry, kinematics, and dynamics; function of tools and end effectors; procedures and constraints for safe operation; global structure of the robot's workspace; as well as status information gathered on-the-fly such as current robot location and configuration and local structure of the workspace. With this information, it is possible to create intelligent robot behavior in which decision making is based on evaluations of the state of the world and the state of the robot.

The Workspace Modeler will be based on a commercial robot simulation and modeling package (TELEGRIPTM by Deneb Robotics, Inc.) that has been adopted for similar applications by several DOE National Labs, possibly complemented by the Interactive Computer Enhanced Remote Viewing System (ICERVS) 3D database being developed under a separate PRDA contract by Mechanical Technologies, Inc. ICERVS is attractive because it uses an object-oriented approach and is thus well suited to D&D work which involves manipulation of objects and operations on structures and surfaces. In general, while implementing this system we will evaluate and employ available technologies under development within the DOE community, including work being

done at Oak Ridge National Labs, the University of Tennessee, Sandia National Laboratories, and Pacific Northwest Laboratories.

In Phase 3, we plan to demonstrate and test the RWV II and its workspace modeling capabilities in a DOE facility that has features and equipment representative of highly contaminated facilities but where radiation levels permit human entry without special protection. This will make it easier to perform controlled tests and to document and observe the machine operations. There is also a higher likelihood that the machine could be decontaminated to free-release levels, so it could be subsequently shipped to other facilities to perform other tasks. A demo in a "warm" (as opposed to "hot") facility would thus provide substantial programmatic benefits at relatively low cost. To date we have identified two potential facilities which meet our requirements as "warm." One is the Integrated Process Demonstration Facility (IPDF) at Oak Ridge and the other is a small research reactor located in Saxton, PA.

1.6 Conclusions and Recommendations

Given the wide range of tasks that must be executed, the weak structure of the settings in which they are to occur, and the diversity of environmental hazards within DOE facilities, it is impossible to build one machine to meet all needs. However, in the short term, versatile worksystems that can combine brute force for heavy work with dexterity for fine manipulation, are able to handle a variety of tools, are reliable for extended use, and are adaptable to a range of work conditions are technically and economically more justifiable.

Also needed are interfaces and telerobotic controllers that allow human operators to make effective use of remote worksystems to execute a broad work agenda, cope with unforeseen circumstances and react to changing situations. Since it is highly probable that D&D scenarios will always require a man-in-the-loop, the utility of the remote equipment will be largely dependent upon how well the man and machine are able to operate together. This ability to work cooperatively will be determined by the fidelity of interfaces between the worksystems and human operators and the extent to which telerobotic controllers can assume responsibility for safe execution of tasks.

Specific conclusions and recommendations from this first phase of work include the following.

- Multiple steering modes are useful for D&D tasks and worth retaining in the RWV II design. Navigational aids and automatic guidance capability should be added for driving control.
- A robot simulation driven by real time joint angle measurements can be used to generate a 3D graphical representation of the robot that allows the operator to quickly assess the robot's configuration.
- Both driving and manipulation can be facilitated by sensing the manipulator's workspace and including information about the robot's proximity to objects in its surroundings in the 3D display.

- Manipulator and tooling performance and efficiency can be improved through more advanced control schemes in which forces at the end effector are measured and fed back to the manipulator control system and/or the operator.
- It would be worthwhile to undertake a program of modifying a much broader set of tools than was used in this effort to gain further experience and to better understand their utility for D&D operations. Such a program can probably be executed at a modest expense and should bring together other tool development/modification efforts within the ER&WM program.
- Use of a single standardized tool interface providing mechanical, electrical and hydraulic connections that can be made and broken remotely will facilitate tool interchange.
- The operator interface design should emphasize the aspects of worksystem control that are used most often without comprising access to secondary functions. The interface should also provide rich information about the state of the robot and its workspace without overwhelming the operator.
- Dexterous, light-duty worksystems of similar scale to the RWV can readily maneuver through settings like DOE weapons production facilities and have the reach perform a wide range of tasks relevant to D&D within them.
- Increased modularity of design can increase the relevance of mobile worksystems to larger numbers of sites. To effectively control the numerous worksystem motions and monitor its status, the mobile worksystem should have an onboard real time controller.

Next generation mobile worksystems should give DOE a useful tool that can be adapted to site needs and quickly put into practice. Modularity of components, both hardware and software, is essential since task requirements, infrastructures, and operating constraints vary across the complex and will change with time as facilities transition to re-use. At this point in time, specific needs for D&D are in many respects poorly defined: regulations and policies are in flux, standards for "how clean is clean?" do not yet exist, and overall strategies for meeting D&D requirements in the face of budget limitations are lacking. Furthermore, prior experience in D&D operations is limited, making it difficult to plan, cost, and schedule D&D activities that will span the DOE complex for the next two decades.

There are several technologies currently available or under development that can be advantageously applied to mobile worksystems for D&D. Advanced operator interfaces, sensing, data processing and modeling capabilities for workspace modeling, manipulator control schemes, tools and other relevant technologies are being developed both within and outside of DOE. It is therefore imperative to stay abreast of these development programs and be responsive to the needs of DOE sites as future worksystems are developed.

2. Introduction

2.1 Background: Design of the Original RWV

The Remote Work Vehicle (RWV) is one of three mobile teleoperated systems developed for accident recovery activities at Three Mile Island Unit-2. It was conceived to fulfill a specific set of task objectives and had unique attributes for operation in the Reactor Building Basement (RBB) where radiation exposure precluded the use of a human workforce. The RWV design was based on the experience of predecessor robots at TMI-2 and technologies, system philosophies and operating methods proven to work in other adverse environments.

At the time of the TMI-2 accident, existing remote worksystems for nuclear applications were poorly matched to the work scope and operating conditions for RBB recovery. GPU Nuclear, Inc., thus commissioned the development of a new remote system, the RWV, for recovery efforts in the RBB. In addition to access and maneuvering requirements, performance capabilities specified for the RWV included the ability to deploy tooling from floor to ceiling (22 feet high) for tasks including de-watering and sediment removal, concrete demolition, steel structure dismantlement, surface decontamination and coating application, and material transport. Goals were also set for reliability (assured egress), operability (remotely, by a three person team), decontaminability (wash down with high pressure borated water), and extensibility (for additional tasks).

The RWV's design philosophy was influenced by operating experience and component technology of its predecessor TMI-2 reconnaissance robots, principally the Remote Reconnaissance Vehicle (RRV) and Remote Core Sampler (RCS). Where possible, RWV development sought pre-existing hardware solutions and successful system philosophies from other industries to expedite the development and assure performance. Many conditions in the RBB were similar to the environments in which undersea robots and construction equipment operate routinely. The undersea environment is dark and wet, operators are very remote from the equipment, and successful operation is economically justified despite formidable difficulties. Undersea operations demand reliable equipment over prolonged missions and achieve such objectives through overrating components and effective sealing against water intrusion. Like many nuclear applications, operation and maintenance of undersea remote equipment are performed in the field and systems must therefore be understandable, diagnosable and repairable by field technicians. Since construction equipment must survive nearly constant exposure to dust, dirt and water along with occasions of falling debris or collisions, construction equipment endurance and ruggedness standards were considered appropriate to the needs of long duration recovery operations in the TMI-2 RBB.

To achieve the required work capability and environmental hardening, the RWV adopted electrohydraulics as its main power source. As vehicle and tooling power requirements increase, electrohydraulic systems begin to have significant size and weight advantages over electric systems. Hydraulic pumps are central power supplies that can support the numerous motions required of capable work equipment and all system power can be focused on a single motion where appropriate. Hydraulic actuators are smaller than electric counterparts of equivalent power, do not typically require gearing (allowing direct-drive and back-drive) and are forgiving in overload and impact tolerance. Many work tools are hydraulic because of the simple conversion of hydraulic pressure to mechanical force.

The reach, stability, and mobility exhibited by construction equipment were also influential. The RWV's telescoping boom takes precedence from high capacity, high reach construction cranes, as does the provision of stifflegs for added stability. The RWV's articulated steering reflects techniques used to achieve mobility on heavy equipment such as rough-terrain cranes, where machine size with respect to the site makes tight maneuvering essential.

2.2 Decontamination and Decommissioning Needs

The environment in which mobile worksystems will have to perform D&D operations range from areas in which no special clothing is needed to protect workers to areas in which the risk of human entry is great. Dangers can include exposure to alpha, beta and gamma radiation; uranium, plutonium, and tritium; volatile organics; acids and caustics; mercury; TRU waste, mixed waste, and asbestos. Facilities in which D&D is likely to occur include uranium enrichment facilities, including gaseous diffusion plants, centrifuge plants and other separation plants; research and production reactors; hot cells, canyons, and vaults; stacks and cooling towers; silos and waste storage tanks; analytical research labs; and weapons production and assembly facilities. Table 2.1 shows a partial list of tasks that might be performed in these facilities; Table 2.2 shows projected D&D needs throughout the complex.

Table 2.1 D&D Work Tasks

Work area	Tasks
Characterization & Monitoring	<ul style="list-style-type: none"> • radiological and other contaminant mapping • personnel monitoring • installation of <i>in situ</i> sensors and monitors • real time screening of radionuclei • sample acquisition
Decontamination	<ul style="list-style-type: none"> • equipment & pipe cleaning • concrete washing & surface removal • coating application • sludge and residue removal
Dismantlement	<ul style="list-style-type: none"> • disassembly of processing equipment • pipe cutting • drain and vent clearing
Waste handling & Minimization	<ul style="list-style-type: none"> • size reduction of equipment • packaging, handling and waste preconditioning • transport of pipes & equipment • dust & aerosol suppression

Table 2.2 DOE D&D Needs¹

PROBLEMS	Alpha Contamination	Beta/Gamma Contamination	Uranium	TRU Waste	Soils/Understructures	Production Reactors	Research Reactors	Separation Facilities	Hot Cells	Gaseous Diffusion Plants	Weapons Production Facilities	Weapons Production Facilities	High Risk Facility	FFA & FPCA Commitments	High Priority Maintenance Costs	D&D Needs Assessment	Hazardous Waste	Mixed Waste	Trium Phys. Disposal	NEPA Requirements
DOE Sites																				
Argonne East	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Brookhaven	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
ETEC	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Fernald	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FUSRAP	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Grand Junction	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Hanford	●	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
INEL	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
K-25	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Kansas City	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
LANL	●	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
LBL & SLAC	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
LLNL	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Mound	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
NTS	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
ORNL	●	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Paducah	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Panlex	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Pinellas	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Potomac	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
RFP	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
SNLA	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
SNL-L	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
SAP	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Weldon Springs	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
West Valley	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Y-12	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Legend:

- Serious Problem
- Moderate Problem
- Relatively Minor Problem
- X Not Determined

Given the wide range of tasks that must be executed and the diversity environmental hazards across facilities, it is unlikely that one worksystem configuration can meet all needs. However, by designing versatile worksystems that can adapt to a range of work conditions and settings, it should be possible to address a large part of the work agenda. Such worksystems should handle a variety of tools and perform a wide range of tasks, should combine brute force for heavy work with dexterity for fine manipulation, and should be reliable for extended use.

Likely scenarios for near term use of remote worksystems focus on strategies for taking unused facilities into a phase of surveillance and monitoring in which they will remain until rigorous D&D plans are developed. Surveillance and monitoring can be facilitated by *de-inventorying*, in which radioactive materials are removed from the area to reduce radiological hazards and requirements for physical security, and *de-activation*, in which the area is decontaminated to the lowest level reasonably achievable by cleaning, containing, shielding and eliminating “hot spots” through dismantlement and highly selective (“surgical”) removal of equipment. These activities will lower the cost of long term surveillance and monitoring by reducing requirements for worker protection.

Applying mobile worksystems for use in de-inventorying and de-activation has several advantages:

- Component technologies for D&D can be developed, tested and proven in real operations in real facilities.
- Worksystems can be demonstrated on a smaller scale than full D&D activities, allowing expertise and experience to be developed at lower cost and with less risk.
- A knowledge base of cost and time factors associated with remote worksystem operation can be created to help devise long term D&D plans and cost estimates.

2.3 D&D Task Analysis

To develop an understanding of the complexity of the sites and of the tooling requirements, we analyzed D&D of a hypothetical pump room containing concrete floors, walls, ceilings, a floor drain, lighting system, fire suppression system, several large pumps with pipes penetrating the walls, wire trays with cables, and debris including sludge and assorted small pieces (chairs, stools, tool box). The pump room we envisioned presented a very complex set of requirements. The room first had to be surveyed to determine the extent and type of contamination present, after which each sub-system was to be decontaminated or dismantled and removed. Finally, the survey was to be repeated to confirm successful decontamination. The order proposed for this process is detailed in Table 2.3.

Table 2.3 D&D Task Breakdown for a Hypothetical Facility

1. Enter facility
 - 1 a. Grasp door handle
 - 1 b. Open door
 - 1 c. Enter room
 - 1 d. Close door
2. Survey the room for contaminants
 - 2 a. Pick up sensor tool with Manipulator
 - 2 b. Maneuver vehicle to areas to be checked
 - 2 c. Move sensor to proper stand-off distance/take reading
 - 2 d. Move down or over designated distance/take reading
 - 2 e. Determine classification of pipe/floor/wall
 - 2 f. Put down sensor
3. Remove standing water/sludge and block floor drain
 - 3 a. Pick up vacuum tool with manipulator
 - 3 b. Vacuum up standing water/sludge
 - 3 c. Block the floor drain
4. Remove loose debris
 - 4 a. Using manipulator pick up and place in barrels all loose debris
 - 4 b. Cut into manageable sizes all oversized loose objects
 - 4 c. Remove barrels from containment using lift
5. Remove all overhead services (lighting, fire suppression, wire trays, pipes)
 - 5 a. Determine service to be cut
 - 5 b. Select tool with manipulator or badger
 - 5 c. Approach cut point with vehicle
 - 5 d. Deploy stifflegs
 - 5 e. Position boom and angle boom platform
 - 5 f. Apply manipulator or pre-tension foot to service
 - 5 g. Cut with grinder, sheers, or saw as necessary
 - 5 h. Lower or drop pipe to floor
 - 5 i. Place in barrels and remove
 - 5 j. Retract stifflegs
 - 5 k. Repeat until finished
6. Remove all lower services (pipes, pumps, drains, power supply lines)
 - 6 a. Determine service to be cut
 - 6 b. Select tool with manipulator or badger
 - 6 c. Approach cut point with vehicle
 - 6 d. Position boom and angle boom platform
 - 6 e. Apply manipulator or pre-tension foot to service
 - 6 f. Cut with grinder, sheers, or saw as necessary
 - 6 g. Place in barrels and remove
 - 6 h. Grind bolts off remaining pumps/equipment
 - 6 i. Attach chains for towing very large equipment as necessary
7. Wash/Scarify walls, floors, & ceilings; seal walls, floors, ceilings
 - 7 a. Position vehicle parallel to wall
 - 7 b. Select tool with manipulator or badger
 - 7 c. Tool power on
 - 7 d. Raise/lower boom
 - 7 e. Tool power off
 - 7 f. Traverse to side
 - 7 g. Lower/raise boom
 - 7 h. Repeat until entire room painted/washed
8. Remove secondary waste
 - 8 a. Pick up large debris
 - 8 b. Vacuum up remaining room contents
9. Survey the room for contaminants
 - 9 a. Pick up sensor tool with Manipulator
 - 9 b. Maneuver vehicle to areas to be checked
 - 9 c. Move sensor to proper stand-off distance/take reading
 - 9 d. Move down or over designated distance/take reading
 - 9 e. Determine classification of pipe/floor/wall
 - 9 f. Put down sensor

Each step above can be mapped to several tools that would be needed to accomplish the task, as shown in Table 2.4. Most tasks require more than one tool and almost all tasks involve packaging

and transporting materials. In many tasks, several candidate tools could be applied. For example, the grinder and cutting saw are essentially interchangeable, as are H₂O and CO₂ scarifiers.

Table 2.4 Tools and Operations Map

	Operation #									
Tool	1	2	3	4	5	6	7	8	9	Total uses
Manipulator*	X	X	X	X	X	X	X	X	X	9
Samplers*	X								X	2
Core borer	X								X	2
Vacuum			X	X		X		X		4
Water jet scarifier							X			1
CO ₂ scarifier							X			1
Coating sprayer*							X			1
Grinder*		X		X	X	X		X		5
Cutting saw*		X		X	X	X				5
Shears*				X	X	X		X		4
Drill	X	X				X			X	4
Breaker		X			X	X				3
Barrel/Hook*		X	X	X	X	X		X		6
Towing apparatus				X		X				2
Compactor				X	X	X				3
Crow bar*		X			X	X				3
Shovel			X	X		X	X			4
Container carrier			X							1
Total tools required	4	7	5	9	8	12	5	5	4	

* indicates tools that were selected for RWV Phase 1 development

The operation requiring the least number of tools is room/sub-system characterization (steps 1 and 9); the most complex task is removal of floor services. A simple way to measure the utility of each tool for the hypothetical D&D job is to count the number of how many sub-tasks it is used for, as shown in Table 2.5.

Table 2.5 Tool Utility for D&D of the Hypothetical Facility

Tool	Number of uses	Rank
Manipulator	9	1
Barrel & Hook	6	2
Cutting tool (grinder or saw)	5	3
Vacuum	4	4
Shovel	4	
Shears	4	
Drill	4	
Chipping hammer	3	5
Crow bar	3	
Compaction tool	3	
Towing Apparatus	2	6
Core borer	2	
Sampling/sensing device	2	
Water jet scarifier	1	7
CO ₂ scarifier	1	
Coating sprayer	1	
Container carrier	1	

From the above table, developed a “short list” of tools use in Phase 1 testing of the RWV which included a manipulator, a grinder, a reciprocal saw, a hydraulic shears, a paint sprayer, a crowbar, a barrel lifter and a bracket for positioning characterization sensors.

2.4 Report Organization

At the outset of the program, we established a set of criteria for evaluating the results of each phase. The criteria for the first phase of the project are listed below with reference to the section in this report in which each is discussed.

Criterion: *Descriptions of near term D&D mission scenarios, task specifications and mobile worksystem requirements are developed.*

DOE’s planned D&D needs and requirements are discussed in sections 2.2 and 2.3 above. Section 7 presents conclusions and recommendations.

Criterion: *RWV I and its new console, controller and tooling are operational as an integrated prototype system testbed.*

Section 3 gives a description of the worksystem with emphasis on the console, controller, software and tooling upgrades developed in Phase 1.

Criterion: *The facility in which the next generation mobile worksystem will perform a "hot" test is identified.*

Section 6 presents future development activities including plans for testing in Phase 3 of the project.

Criterion: *The testbed is used to perform a series of representative D&D tasks in cold tests and the results are documented.*

Sections 4 presents our Phase 1 testing program the results of which are discussed in Section 5.

3. Worksystem Description

The RWV incorporates the following major components: a wheeled *locomotor* that transports and houses on-board components, a *boom* assembly that extends tooling into the work zone, a seven degree of freedom master/slave *manipulator* that deploys a variety of light tools, a *heavy tool deployment mechanism* that positions larger tools, a *real time computer system* that controls and coordinates motions, a *hydraulic system* that powers many of the robot's actuators and tools, a seven camera *video system* for remote operation, *on-board electronics* that route power and signals and monitor robot status, a *tether management system* that conveys power and signals between the robot and off-board components, an off-board *power/signal distribution unit* (PDU) and an off-board *control console* from which a single operator controls all robot functions. General specifications of the RWV are presented in Table 3.1.

The RWV's work capabilities are based on an array of tooling that is deployed by a master/slave manipulator and a heavy tool deployment platform, the "Badger," both of which ride on a tilting, telescoping boom assembly. The manipulator supports tasks that require dexterous positioning and is able to carry a 55 pound payload throughout its work envelope. The Badger tool deployment mechanism supports heavy or high-reaction tooling and supports payloads of up to 400 pounds. Tools deployed from the manipulator include a grinder for metal cutting, a reciprocating saw used to cut pipe or structural steel, a sprayer for low pressure washing and applying sealants surfaces, a sensor bracket for mapping contaminants, and non-powered tools (a crow bar, and a barrel hook to transport waste barrels). Larger tools deployed directly from the Badger include the grinder and a pair of hydraulic shears.

Table 3.1 RWV General Specifications

Weight	~11,000 lbs.
Dimensions	
length (overall)	8.7 ft.
width	3.5 ft.
height (boom stowed)	7.0 ft.
vertical reach	25.8 ft.
horizontal reach	13.5 ft.
Hydraulic System	
pump number & type	two variable displacement
input	7.5 HP electric motors
nominal operating pressure	2400 psi
output flow (total of both pumps)	9 gpm
fluid	UCON WS-34 (water soluble)
Electrical System	
means of delivery	multi-conductor tether
input power requirements	30A @ 480 VAC, 3Ø & 15A @ 120 VAC, 1Ø
Communications System	
digital telemetry	(2) twisted wire pairs
digital protocol	ethernet (10BaseT)
manipulator telemetry	dedicated RG-59 coax
video	(7) RG-59 coaxes

Work in Phase I concentrated on returning the system to fully operational status and upgrading several functions with current technologies. The next section gives a brief overview of the RWV system; extensive work was done on the control console, control electronics, software and tooling.

3.1 Worksystem Overview

The RWV robot is pictured in Figure 3.1 and Figure 3.2. The locomotor consists of a welded stainless steel structure with four independently driven and steered wheels. Two motor/pump sets are mounted on either side of the body which also serves as a hydraulic reservoir. Four stifflegs, one at each corner of the frame, provide increased stability when needed. Structural members and housings are predominantly constructed from polished stainless steel or fine finish aluminum; wherever this standard could not be met, exterior surfaces are painted or anodized to improve decontaminability. Further details on the locomotor and hydraulic system are presented in Sections A.1 "Locomotor" and A.5 "Hydraulic System".

The boom assembly mounts to the locomotor near the rear of the robot. It has three degrees of freedom: rotation of its base, telescopic extension, and a second rotation between the boom tip and the tooling platform. Together these motions give the RWV a large work envelope, as shown in Figure 3.3. Further details on the locomotor are presented in Section A.2 "Boom". Tools are deployed from the tooling platform which carries the manipulator and the "Badger" heavy tool deployment mechanism. See Section 3.5 for a detailed description of the tooling suite.

The tether management system consists of 120 ft. of tether, a reel with integral slip ring pack mounted at the rear the RWV and a level wind capstan that guides the tether on and off of the reel and prevents entanglement. The reel pays out, retrieves, and stores tether as the robot drives. Further details on the tether are presented in Section A.3 "Tether Management".

There are seven cameras on the RWV strategically located and positionable to give the operator all the views necessary for safe operation of the robot and observation of work tasks. There are two main cameras, three manipulator cameras, one boom-top camera and one rear camera. All cameras on the RWV are color CCD cameras with electronic shutter, automatic gain and auto-iris lenses. Each camera is enclosed in a submersible cylindrical housing to which one or two lights are attached. Further details on the video system are presented in Section A.4 "Video and Lighting"

The off-board power/signal distribution unit (PDU) is between the console and the robot. Remotely controlled switching components within the PDU connect externally supplied 480 VAC, 3Ø and 120 VAC, 1Ø electrical power to branch circuits on-board the RWV. The PDU also serves as a junction point for digital telemetry between the console and robot and for video signals from the robot to console displays.

Figure 3.1 The Remote Work Vehicle

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Figure 3.2 Enhancements to the Remote Work Vehicle

Figure 3.3 RWV Work Envelope

3.2 Control Console

The RWV is remotely operated from a console (Figure 3.4) using multi-mode joysticks for locomotion and boom functions, a master arm for manipulator control, switches for camera and lighting control and reconfigurable “soft” controls located on a touchscreen for all auxiliary functions. Control elements are designed to minimize operator fatigue, are grouped by function and are software reconfigurable as the control needs change. Views provided by the on-board cameras can be displayed four at a time or as a single image on a high resolution monitor. The robot’s configuration can also be viewed in a 3D graphical simulation on a separate monitor which also displays critical status parameters measured by on-board sensors.

Figure 3.4 RWV Operator Console

3.2.1 Operator Panel – Hard Controls

The operator panel provides a location for all of the buttons, switches and joysticks used to control the primary robot functions. A brief description of each is provided below. (The numbers in parentheses refer to labels in Figure 3.4).

Figure 3.5 Operator Panel – Hard Controls

- Keyswitch (1) – Located in the upper left hand corner of the console, the keyswitch is used to enable power to the console, on-board computer and related electronics, and on-board cameras.
- Emergency Stop (2) – Located at the top center, the E-stop allows quick shutdown of all robot motions.
- Audio Volume (3) – Located in the upper right of the console, the audio volume knob allows adjustment of the volume of the audio feedback from the robot.
- Boom Mode Buttons (4) – The two buttons to the right of the boom joystick control the boom mode. In *joint* mode, the operator has independent control of each joint of the boom. In *coordinated* mode, the boom motions are coupled through software so that the operator can move the boom tip vertically or horizontally.
- Boom Joystick (5) – The left joystick controls boom motions and has a three degrees of freedom, two thumb operated buttons and a trigger that acts as a safety switch and must be pulled to enable the joystick. The functions of the various motions of the joystick are described in Table 3.2.

Table 3.2 Boom Joystick Functions

Boom Joystick Motion	Resulting Action in Joint Motion Mode	Resulting Action in Coordinated Motion Mode
Up	Rotate base joint down	Boom tip vertically down
Down	Rotate base joint up	Boom tip vertically up
Left	Retract boom	Boom tip horizontally in
Right	Extend boom	Boom tip horizontally out
Rotate Left	No function	No function
Rotate Right	No function	No function

- Drive Mode Buttons (6) – The two buttons to the left of the drive joystick control the drive mode. In *curvilinear* (or four wheel steer) mode, when the operator turns the joystick, the front and back wheels are directed in opposite directions. This allows the robot to make tight turns and even turn in place. In *translational* (or “crab” steering) mode, all four wheels are pointed in the same direction, allowing the robot to translate along straight lines any direction without changing it’s orientation.
- Drive Joystick (7) – The right joystick, physically identical to the boom joystick, is used to drive the robot. Its trigger also acts as a safety switch and must be pulled to enable the joystick. The function of the various motions of the drive joystick are described in Table 3.3.

Table 3.3 Drive Joystick Functions

Drive Joystick Motion	Resulting Action in Curvilinear Driving Mode	Resulting Action in Translational Driving Mode
Up	Drive forward	Drive forward
Down	Drive backward	Drive backward
Left	No function	Drive left
Right	No function	Drive right
Rotate Left	Turn front wheels left and back wheels right	No function
Rotate Right	Turn front wheels right and back wheels left	No function

- Camera Controls (8) – These controls allow the operator to adjust the zoom, focus, iris, pan, tilt and lighting level of the cameras. Since the monitor can

display four views, there are four separate sets of controls, one corresponding to each view. Any camera can be mapped to any view using the touchscreen.

- **Manipulator Master Control (not shown)** – The manipulator is controlled using a “master arm”, a mechanical linkage that is kinematically equivalent to the manipulator on-board the RWV. (The latter is also referred to as the “slave” arm, since motions of its joints exactly duplicate, i.e., are slaved to, joint angles of the master arm.) The master arm is mounted on a pedestal next to the console and can be placed on either side of the console depending on operator preference. A hand-held pendant with a keypad is connected to the master arm and is used to turn the manipulator’s main hydraulic valve on and off, to bring the master and slave arms into spatial correspondence at power up, and to invoke special modes of operation such as teach/playback and reduced degrees of freedom.

3.2.2 Touchscreen – Soft Controls

The touchscreen provides soft controls organized as a hierarchical set of menus for functions that are used infrequently. A main menu located at the bottom of the touchscreen contains several soft push-buttons that are used to activate particular sub-menus. The active sub-menu is displayed above the main menu and may contain momentary, on/off, or slider controls for the various functions. These functions are summarized in Table 3.4; detailed descriptions of the sub-menus are presented in Section A.6 “Control Console Touchscreens”. There are also sub-menus for console diagnostics, development and debugging that are not used during normal operations.

Table 3.4 Primary Touchscreen Sub-menu Functions

Sub-menu	Function(s)
Power	<ul style="list-style-type: none"> • independent on/off control of the two hydraulic pumps • enabling/disabling of all hydraulic valves
Drive	<ul style="list-style-type: none"> • adjustment of drive and boom motions top speeds
Tooling	<ul style="list-style-type: none"> • control of on-board tooling • assignment of tool control to the footswitch • control the Badger tool positioning mechanism
Video	<ul style="list-style-type: none"> • mapping the on-board video cameras to the four quadrants of the video monitor and their associated camera controls
Stifflegs	<ul style="list-style-type: none"> • control of the four stifflegs independently or as a group
Tether	<ul style="list-style-type: none"> • payout/take-up of tether
Shutdown	<ul style="list-style-type: none"> • shutdown of the console

3.2.3 Audio/Video

The video display on the console is a single high resolution 19" monitor. The input to this monitor comes from a screen splitter that divides the display into four quadrants allowing four different video images to be displayed simultaneously. If desired, any one of the four quadrants can be

selected to fill the entire screen. A 16-input/8-output matrix video switcher is used assign RWV camera views to the video display. Both the screen splitter and video switcher are computer controlled through the touch screen, which allows the operator to map on-board cameras to a desired portion of the video display using touchscreen controls. Each quadrant of the video display has associated with it a bank of hard switches for pan, tilt, zoom, focus and lighting control that are also mapped to the selected camera. A VCR is provided for recording the camera views. (See Figure 3.6)

The audio system consists of two speakers which are connected to two microphones located on the robot providing stereo sound. A graphic equalizer allows the operator to shape the audio signals to eliminate noise or tune in on a specific frequency.

Figure 3.6 Console Audio/Video Block Diagram

3.2.4 Console Electronics

All console computing is performed by an 80386-based (IBM compatible) computer that drives the touchscreen, reads the status of soft and hard controls (except the Kraft master controller), and communicates the status of all console inputs to the real time controller on-board the RWV. All console components are interfaced to the console computer via input boards on a PC backplane; additional custom interface boards are used to filter the joystick output signals and to drive the relays that control the various power circuits in the console and on-board the robot. A schematic showing the general console electronics layout is shown in Figure 3.7.

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Figure 3.7 Console Electronics Schematic

3.3 Control Electronics

The RWV's on-board electronics consists of a real time computer controller, interface components, a power distribution system and several status sensors, as shown in Figure 3.8.

Figure 3.8 On-board Control Electronics Block Diagram

3.3.1 Controller & Interface Electronics

A card cage conforming to the Versa Module Eurocard (VME) standard with 6U board height is mounted in the electronics enclosure and houses all computing and I/O boards for the on-board controller. The on-board controller has two 68030 CPU processor boards. The first CPU's primary functions are to interface with the control console, monitor console state changes, send updates to the 3D graphical display and plan motion trajectories. The second CPU controls the servo loops and acquires sensor data. The processors communicate with each other and other boards in the card cage through the VME backplane and use an Ethernet connection to communicate with the control console.

In addition to the CPU boards, there are five input/output boards (I/O) in the VME card cage including a custom sensor interface board, parallel I/O board, digital to analog and analog to digital I/O board (DAADIO) and an analog to digital board (A/D). Output signals from all on-board analog and digital sensors enter the custom sensor board and are routed to various other boards in the VME cage. All signals are filtered and shielded from power surges; most of the sensors receive power through the sensor board from the VME power supply. This board also supplies the control voltages to the boom proportional valves and the steering valves and control signals to the solid state relays.

The parallel I/O board has 96 digital signals, both input and output, which control the majority of machine functions. This board is interfaced to a set of digital output modules (Opto 22) used to provide optical isolation between the control logic and the valves and actuators that are controlled. Each digital module is dedicated to a particular group of functions. These functions include: propulsion valves and lights, stifflegs, tether management, cooling, tooling, boom intensifier, Badger functions, camera positioning actuators, camera focus and zoom, and tooling relays. There are also several relays including: the tooling relays switch the 120 VAC from tether to the tooling enclosure on the boom platform, a block of relays that electrically brake the tilt motors on the two navigation cameras and a set of mechanical relays that control the lights.

The DAADIO board serves two main functions, digital to analog conversion to drive the proportional valves that control boom motions and analog to digital conversion of motion encoder signals (potentiometer readings). The A/D board can read 16 analog inputs including the status sensors and then digitally pass the information to the CPU.

3.3.2 Power Distribution

The on-board power distribution network is the means by which all power transmitted through the tether is branched out to the various components on the RWV. All tether power conductors pass through a slip ring package in the tether reel and are terminated at devices and junction terminals in the main electronics enclosure. Two separate three phase wire circuits power the electric motors that drive the hydraulic pumps. Independent two-wire 120 VAC circuits power the on-board controller, the video system, hydraulic valve supply, electronic enclosure cooling fans, and electrical tools. The latter three are controlled by a relay driven by a signal from the sensor board.

3.3.3 Status Sensors

Within the enclosure are two damped pendulum potentiometers which serve as pitch and roll sensors to allow leveling of the machine when the stifflegs are being deployed. Other status

sensors measure hydraulic fluid temperature, hydraulic system pressure, reservoir fluid level, motor overheating, hydraulic filter clog status, electronics enclosure temperature and bump sensors on the top of the boom. All these sensors relay information to the control console and signal the operator when they are triggered or reach an “out-of-bounds” condition.

3.3.4 Manipulator Transceiver

A transceiver on-board the RWV communicates to the manipulator’s control unit in the console receiving commanded joint angles and transmitting feedback signals that indicate joint positions. This unit also contains electronics that drive the manipulator’s servo valves and convert analog voltages from potentiometers in each manipulator joint into digital signals. (The RWV’s controller performs a similar conversion so that the manipulator configuration can be shown in the console’s 3D graphical display.)

3.4 Software

The real time controller for the RWV I test bed is designed for modularity and reusability. The software consists of two distinct systems, one running on the robot and the other running on the console. All code is written in the “C” programming language with consideration given to building a generic software structure and runs under the VxWorks (Wind River Systems) real time operating system. The architecture of the RWV software system is shown in Figure 3.9; a brief explanation of each software module is provided in Table 3.5.

Figure 3.9 RWV I Software Architecture

Table 3.5 Modules of RWV I Software Architecture

Module	Description
Console Driver	Performs touch-screen redraw/update, menu handling with alphanumeric I/O, analog and digital I/O, and telemetry I/O through the telemetry module interface
Telemetry Module	Provides reliable communications between the console and the vehicle and provides data type conversion and buffering
Task Executive	Maintains system state and communicates through a telemetry module to the Console I/O controller; calls lower level functions as the result of changes in the state of the console controller or the system
Application Specifics	Set of functions that provide the joint and cartesian level functionality to the upper levels of the architecture.
Joint Mover	Accepts relative or absolute commands that affect changes in the position or velocity of a joint and returns state from the servo'd axis.
Cartesian Mover	Generates motion plans in specified coordinate systems; accesses trajectory planner, kinematics, and scaler to perform coordinate transformations
Kinematics	Performs forward and inverse kinematic calculations
Scaler	Scales motions
Servo Axis	Implements the lowest level servo loop according to particular control law; also generates warnings and checks for exceptions
Sensor Driver	An interface to sensors in the control system; also compensates for any non-linearities and performs units conversions
Actuator Driver	Interface to an actuator in the control system; also compensates for any non-linearities and performs unit conversions
Local Device	Software interface to a local I/O board
Remote Device	Software interface to a remote interface board
Exception Handler (Service)	Reacts to exceptional states of the system (errors) by notifying relevant modules of the occurrences
Arbitrator (Service)	Allows queue access to a mechanism or set of mechanisms so that the possible contention between multiple user applications is resolved in a logical manner
Trajectory planner (Service)	Provides parametric trajectory interpolation services to both the joint and cartesian motion systems.
Blackboard (Service)	A means by which to convey sensor, actuator, and miscellaneous data to any external requesting modules
Igrip Interface (Service)	Creates an interface to the IGRIP simulation software. This interface updates a 3D model of the robot on a computer screen

3.5 Tooling

Seven tools and two deployment systems were developed for performing D&D tasks with the RWV. All tools were adapted for remote operation by modifying shelf available tools to interface with the robot. The RWV tooling suite includes a hydraulic grinder, hydraulic shears, an electric reciprocal saw, an electric paint sprayer, a crow bar and a barrel lift. In addition, a tool which simulates a radiation assessment sensor has been developed, using a temperature sensor as a surrogate for a geiger counter or similar device. Specifications of the RWV tools are presented in Table 3.6.

Table 3.6 RWV Tool Specifications

Tool	Manufacturer/Part#	weight (lbs.)	Type	Power requirements
Manipulator	Kraft/Grips-9020	130	hydraulic	3 gpm @ 1500 psi
Badger	CMU/RWV-T1	170	hydraulic	1 gpm @ 2000 psi
Grinder	Stanley/GR29	10	hydraulic	1.5 gpm @ 2000psi
Reciprocating Saw	Milwaukee/6527	9	electric	8 A @ 120 VAC
Airless Paint Sprayer	Hausfeld/4ZC74	49	electric	9A @ 120 VAC
Pipe Shear	Hurst/JL-150	37	hydraulic	1 gpm @ 5000 psi
Crow Bar	Grainger/GNB24	4	N/A	–
Barrel Lift	Grainger/5W683	15	N/A	–
Temperature Sensor	CMU/RWV-T2	8	electric	100 mA @ 5 VDC

The deployment platforms consist of a Kraft Telerobotics Grips Manipulator and the Badger, a custom-made electrohydraulic mechanism for positioning heavier tools. These are shown in Figure 3.11. Each tool is mounted to a standard interface consisting of a plate with six holes along the edges. The plate can then either be mounted to the Badger or to an H-handle (Figure 3.11) designed to be grasped by the manipulator gripper. As currently configured, the robot can carry up to three tools on each mission, though only two tools can be stowed on the Badger at any one time. The Badger is also equipped with a tool “holster” that allows the operator to pick up and put down any tool that can be gripped by the manipulator.

Figure 3.10 Manipulator and Badger (shown carrying hydraulic shears)

Figure 3.11 H-handle Tool Interface

3.5.1 Manipulator

The Grips Model DGM 7A manipulator system is a general purpose master/slave arm designed for work underwater and in other hostile environments. The manipulator operates as a position controlled, closed-loop servo system in which movements of the master arm, a mechanism that is kinematically identical to the slave arm, are duplicated by the slave arm. In addition, the control system has a teach/play back capability that allows sequences of motions to be recorded for playback at a later time. Teach/play back and set up and calibration functions are accessed through a keypad on a pendant connected to the master arm. (See Figure 3.12)

The slave arm is a seven degree of freedom electrohydraulic manipulator with three arm motions, three wrist motions and a gripping motion. All motions, with the exception of the wrist rotate and the gripper, utilize rack-and-pinion transmissions driven by rotary actuators. The wrist rotate actuator consists of a piston type motor and gear box which provides the added benefit of a continuous wrist rotation. A double-acting cylinder is used to open and close the gripper. Each actuator is controlled by a hydraulic servo valve mounted on a manifold that is integral to the manipulator base. The arm and wrist motions are controlled by independent servo loops that include potentiometers coupled to the actuators for position feedback. Opening and closing of the gripper is open loop as is continuous wrist rotation.

Specifications of the manipulator are presented in Table 3.7 and Table 3.8; its work envelope is shown in Figure 3.13.

Figure 3.12 Manipulator System Components

Table 3.7 Manipulator Specifications

Maximum Extended Reach	51 inches
Lift Capacity at Full Extension	55 lbs
Degrees of Freedom	6 plus gripper
Standard End Effector	parallel jaw gripper
Gripper Opening	4 inches
Gripper Closure Force	200 lbs
Weight	130 lbs
Hydraulic Operating Pressure	1500 psi
Hydraulic Flow Requirements	3 gpm
Hydraulic Filtration	25 micron absolute

Table 3.8 Manipulator Joint Motions

Axis	Total Excursion	Angular Slew Rate
Shoulder Azimuth	180°	80°/sec
Shoulder elevation	120°	65°/sec
Elbow Pivot	110°	50°/sec
Wrist Pitch	100°	100°/sec
Wrist yaw	105°	115°/sec
Wrist Rotate (Slaved Mode)	180°	200°/sec
Wrist Rotate (Continuous Mode)	Continuous	35 RPM

Figure 3.13 Manipulator Work Envelope

3.5.2 Badger

The "Badger" is designed to deploy tools are heavier or require greater reaction force than the manipulator's rated payload. The Badger's main component is an 8" aluminum box section with a pair of tool mounting plates mounted either side and an internal fly section that telescopes outward to pre-tension the mechanism against a wall, pipe or other external structure. The tool mounting plates ride linear bearings and are extended into the workspace by hydraulic cylinders. The main box beam is mounted to a hydraulic rotary actuator capable of 180 degrees of rotation which is then mounted to the underside of the RWV tooling platform. All hydraulic control valves to operate the Badger (as well as two hydraulic tools) are contained in a manifold mounted atop the main box section.

Figure 3.14 Badger Tool Deployment Mechanism

3.5.3 Hydraulic Tools

The hydraulic grinder is a modified Stanley Grinder which can handle up to a 9" cutting disc. The abrasive discs can be used to cut both concrete and metal. The grinder can be used with both the Badger and the manipulator (Figure 3.15).

The hydraulic shears are adapted from the Hurst JL-150 "jaws of life" equipped with "Bettis Blades" developed specifically for cutting stainless steel pipe in nuclear reactors. These blades are designed to cut stainless steel pipe up to 2.5" but are also useful for cutting other metal shapes (conduit, wire, etc.) straight 15" blades are also available. Because the shears require low flow and high pressure (1/2 gpm at 5000-8000 psi.), a hydraulic intensifier capable of producing a 6:1 pressure increase is plumbed ahead of the shears' input line to boost the RWV's system pressure. The shears are shown in Figure 3.11.

3.5.4 Electric Tools

The reciprocal saw is a modified Milwaukee Super Sawzall. The saw can accommodate up to a 12" blade and has a 1 1/4" stroke. Blades are available for cutting wood, metal (ferrous and non-ferrous), concrete, plastic, rubber, and plaster. This versatile tool can be used on either the Badger or the manipulator.

The paint system is adapted from a commercial airless paint sprayer manufactured by Campbell Hausfeld. The system consists of a fluid reservoir and pump, which hang from the tooling platform and a spray nozzle modified to be handled by the manipulator gripper. This system can

be used with several different types of paints and other coating materials and can deliver up to 1/3 gallon per minute; coverage and speed of application are determined by the coating being applied and the shape of the area being coated.

Figure 3.15 Pipe Cutting with the Grinder

The "sensor tool" is designed to test sensing operations that typify radiological and other characterizations. It consists of a sensor housing designed to accommodate probes with diameters up to two inches (for the purposes of demonstration, a temperature probe was used as a surrogate for radiation and other contaminant detectors) and a switch used to indicate contact with the object being scanned. The distance that the contact switch protrudes from its housing can be adjusted to vary the sensor's stand-off distance. Sensor readings are sent back to the on-board computer via a five conductor cable connected to a waterproof connector at the boom platform.

3.5.5 Non-Powered Tools

The crow bar is a 24" steel pry bar and hook. The crow bar is mounted to a tool plate and can be adjusted to be used either as a hook or a pry bar on either the Badger or the manipulator. The barrel lifter is designed to lift full, sealed 55 gallon drums and carry them out of containment. The barrel lifter is a rim clamp and lever type barrel lifter and is mounted by a chain to the underside of the boom tip platform. The limiting factor in lifting barrels is the capacity of the boom, which is approximately 500 lbs at maximum reach and 800 lbs when retracted.

4. Testing Program

The Phase 1 testing program was designed to produce qualitative data on the effectiveness of the worksystem testbed for D&D operations. Testing results will be used to develop a better understanding of the capabilities of the RWV relative to needs, requirements and constraints of D&D within DOE facilities and to guide the design of a next generation mobile worksystem, the RWV II, in the second phase of the program.

4.1 Methods

4.1.1 Testing Facility

For the Phase 1 testing program, we constructed a testing facility that is representative of DOE facilities in which mobile worksystems will operate in the future. The workspace is an industrial setting that contains structures, equipment, piping, valving, and ductwork found in processing and assembly plants. The mockup was designed to be easily reconfigured to test driving and manipulation in several operating scenarios and to allow safe operation of the robot.

The testing facility is divided into three separate areas: a work area, a viewing area, and a console area (see Figure 4.1). The work area is a fully enclosed, framed plywood structure, measuring 28 x 40 feet, that provides physical isolation of the working robot from the console and viewing areas. The south wall and the majority of the east wall are 16 feet high and have built-in fixtures for mounting piping and conduit both horizontally and vertically; other structures within the work area include: an elevated platform along the east wall, a freestanding double door frame, freestanding walls, and a 12-foot tall "tank" mockup. Testing and demonstrations can be viewed from the north and west walls which have windows. The console area is immediately adjacent to the work area and is situated to allow line-of-sight operation. (All testing was performed in teleoperated mode, i.e., without direct view of the robot, however, having line-of-sight is useful for operator training and debugging.) Midway through the testing program, we mounted a camera above the console area to provide a "bird's eye view" of the work area at the console. This was primarily a safety consideration and a means to conveniently videotape each test, though having the robot or a human worker place such a camera during operations in a real facility is feasible.

4.1.2 Personnel

Four project personnel were selected to serve as primary operators throughout the testing program. The operator's primary responsibility was to perform the task to the best of his/her abilities and report on the experience, providing complete and accurate feedback on the usefulness of the machine and the console functions. None of the operators had any significant teleoperation experience nor had they operated heavy machinery prior to these tests.

During each test, one of the operators was designated to be test director and was responsible for:

- Set up – placement of objects within the work area; ensuring that the work area is configured identically for each test run; instructing the operators on the nature and objective of the test; preparing videotape recorders.
- Monitoring – recording start, finish and intermediate time intervals (if any); ensuring safety, including emergency shutdown if necessary.

- Documenting – providing the operator with a task evaluation form; ensuring that evaluation forms are completed and logged; recording any failures or other system maintenance issues in the log book; updating videotape labels and logs.

4.1.3 Testing and Data Collection Procedures

The types of tests conducted fell into three primary categories. In an *open test*, the operators were given full knowledge of the test site layout and allowed to directly view the machine during testing. This type of test was used primarily for operator training. In *schematic tests*, the operator was given diagram of the workspace but did not actually view the site prior to executing the task. Schematic tests required the operator to mentally map the diagram to the site as viewed through the RWV's cameras to determine where the objects are actually located and, thus, probably best represent how most operations in real DOE facilities will be conducted. In *blind tests*, the operator was given no advance information about the work area and no schematic diagram. These represent tasks in which a mobile worksystem makes first entry into an area so contaminated that human entry is prohibitively expensive or dangerous, e.g. work in a situation like the Three Mile Island Reactor Building Basement. A fourth type of test, a *control test*, was a complex schematic test repeated by each operator several times over the course of the testing program. *Control tests* were used to evaluate overall proficiency in operating the worksystem to execute a particular work agenda. All tests were performed at least once by each operator.

For each test we created a written task description detailing the operation(s) to be performed, a photograph and/or schematic representation of the test site configuration and a list of task constraints. After completion of a task, each operator filled out an interview form to document:

- their approach to the task and which aspects of the task were most and least difficult;
- worksystem capabilities that were most and least useful for performing the task;
- key features or deficiencies of the worksystem, console and controller; and
- other factors associated with the RWV I's design and operations.

A copy of this form is in Appendix B.

In addition to the evaluation forms, each test was documented in several other ways. Videotaping was used extensively to record worksystem actions in the mockup, operator actions at the console, and teleoperation camera views. In most tests, the "bird's eye" camera view was recorded on a VCR in the console; a tripod-mounted camcorder in the work area was used in some tests. Throughout the testing program, all maintenance performed on the worksystem, console and controller was noted in a log book.

Figure 4.1 Worksystem Testing Facility

4.2 Test Descriptions, Objectives and Results

After executing the tests, we examined the evaluation forms to note what factors most strongly affected performance of the worksystem and the ability of the operators to complete the assigned task. The description, objectives and results of these test are presented below; these results point to more general conclusions about the RWV I's capabilities for D&D operations which are presented in Section 5 "Results and Discussion."

Task #1: Object Recovery

Description: Collect three objects in numerical order (numbered paper targets mounted on the wall) and place them in a container. Three extra targets will be put up as decoys.

Test Objective(s):

- Assess difficulty of grasping and placing objects.
- Assess adequacy of camera perspectives for object grasping and placing.
- Study relative uses of locomotion, boom functions, and manipulation in a task that requires all three.

Results:

- Over half of the task time was spent aligning the robot with the target prior to grasping. A "good" set up configuration for grasping objects within the manipulator's work envelope was lost when the vehicle had to be moved to place objects into a container.
- Grasping was not difficult. (NOTE: damage to the objects was not considered.)
- Judging distance was difficult.
- The slew rates of the main camera pan & tilt actuators was too low. In contrast, the wrist camera was used often since it could be moved rapidly.
- Driving was performed as little as possible; the manipulator (which has the finest motion resolution) was used as much as possible.

Task #2: Slalom Driving

Description: Drive through a room, maneuvering around obstacles placed on the floor.

Test Objective(s):

- Assess adequacy of on-board camera perspectives in avoiding collisions while driving.
- Assess utility of translational and curvilinear driving modes.

Results:

- Judging side clearances was perhaps the most difficult aspect of driving.
- The manipulator wrist camera was very useful during driving; the main cameras were also useful but they move too slowly.
- Translational driving mode was extremely useful; most operators switched between driving modes often.

Task #3: Pipe Grinding

Description: Given a diagram of pipes hung horizontally on a wall and a specific target pipe, cut through that pipe using a 9-inch grinding disk.

Test Objective(s):

- Assess remote operation of the grinder.
- Determine limitations of ability to cut closely spaced pipes.

Results:

- Grinding a horizontal pipe required clearance above and below the pipe about equal to the diameter of the grinding disk
- Grinding was facilitated by locking out the manipulator's waist motion. This helped to prevent binding and assisted in returning to the same cutting groove.
- Force feedback would have improved performance in this operation.
- The main cameras, which have zoom lenses, were useful in observing work progress.
- Use of a foot pedal for on/off control of the grinder worked well.

Task #4: Pipe Grinding and Recovery

Description: Drive into a room, find the "hot" pipe (identified by a paint marking), cut it down with the grinder and place it into the waste barrel.

Test Objective(s):

- Assess system performance while executing a combined driving, dismantling, and debris recovery operation.

Results:

- Picking up the cut pipe from the floor was more difficult than cutting it since each pipe landed in an arbitrary location and orientation.
- Boom motions were preferred over driving motions when positioning the manipulator prior to cutting.
- Placing a pipe into a container was relatively easy.

Task #5: Sawzall Cutting

Description: Cut through a piece of pipe using a reciprocal saw carried by the manipulator.

Test Objective(s):

- Assess remote operation of the reciprocal saw.

Results:

- The reciprocal saw was best used for soft materials such as wood and PVC.
- Keeping the blade in the cutting groove is difficult (several blades were broken during this operation). A mechanism to hold the saw against the pipe would improve performance.
- Use of the foot pedal for on/off control of the saw worked well.

Task #6: Painting

Description: Find a control panel designated on a drawing of the room and paint it, completely covering all surfaces.

Test Objective(s):

- Assess remote operation of the paint sprayer.
- Assess motions needed for painting surfaces in several different orientations.

Results:

- Orienting the robot was far more difficult than actual painting.
- The robot's size made it difficult to achieve some orientations/configurations, particularly for painting the bottom surfaces of man height control boxes.

Task #7: "Pick Up Sticks"

Description: Ten sections of pipe are randomly strewn on the floor of two rooms. Pick up and place into a container as many pipes sections as possible in one hour.

Test Objective(s):

- Assess system performance while executing an involved driving and manipulation task.
- Force the operator to devise a strategy for performing a task quickly.

Results:

- Maneuvering between the two rooms was more difficult than operating in one room.
- The main cameras were more useful in assessing the location of all the objects, though the manipulator's wrist camera provided the most useful perspective for picking them up.
- A camera with a wide angle lens would have helped to more rapidly locate all the pipes and plan effective strategy.
- Only one operator retrieved all ten pipes; all got at least five.
- Some operators carried the container with them, reducing the time spent to retrieve the pipes.
- If the container was upset a great deal of time, up to 10 minutes, was lost righting it.

Task #8: Pipe Following

Description: Locate a "hot" pipe and move along its length, touching the pipe at one-foot intervals.

Test Objective(s):

- Assess ability to collect sensor data in a task analogous to radiological mapping.
- Assess ability to combine locomotion and manipulation to follow a long, straight trajectory and judge spatial dimensions.

Results:

- Once the robot was aligned perpendicular to the pipe, use of translational driving mode to move sideways made this task straightforward.
- Determining distance travelled was difficult.

Task #9: Control Task

Description: Drive down a hallway, turn a corner, down another hallway, turn into a room through a man door, maneuver to a pipe, and cut down a marked piece with the shears.

Test Objective(s):

- Evaluate the operator's ability to control all motions of the RWV.
- Compare each operator's performance over multiple runs of the same task and to determine the general shape of the learning curve.

Results:

- All but one operator reduced his/her overall time to complete this task by ten minutes during the second week and to half their original time in the third week.
- Operators began to fatigue after between 40 and 60 minutes of continuous running.
- Repetition of the same task allowed operators to optimize their strategies to reduce execution time.

Task #10: Valve Manipulation

Description: Locate and shut off two valves. One of the valves is a lever action gas valve, and the other is a rotational water valve.

Test Objective(s):

- Assess ability to constrain forces while manipulating objects.
- Assess motions needed for manipulating objects where orientations are constrained.

Results:

- Controlling forces without any force feedback is very difficult. One circular valve handle was sheared off and one lever action valve was turned past its mechanical stop.
- Positioning the robot was a major part of the task.

Task #11: Pipe Cutting with Two Tools

Description: Maneuver into a room, find a marked pipe and cut it, once using the shears and again using the grinder.

Test Objective(s):

- Compare remote operation of the grinder and the shears for pipe cutting.
- Evaluate the use of a “tool holster” as part of the Badger heavy tool deployment mechanism.

Results:

- The shears are easier to operate but harder to align, since they are deployed by the Badger (the grinder can be positioned with the manipulator).
- Relative to the grinder, the shears can cut pipes that are more closely spaced.
- Once positioned the shears cut pipes up to four times faster than the grinder.

5. Results and Discussion

The RWV is intended to be a versatile mobile worksystem able to perform a wide variety of tasks relevant to DOE's ER&WM mission. Results from individual tests alone are an insufficient basis from which to assess versatility; this section derives more general results on overall worksystem capability by examining the test results as a whole. These results are presented in terms of the worksystem mobility, manipulation, tooling, and operator interface, as well as system configuration.

5.1 Mobility

Driving was a necessary aspect of every task performed and accounted for a significant fraction of the overall task execution time. We did not attempt to rigorously quantify the amounts of time spent driving versus positioning the boom, etc., since our selection of tasks, the limited size of our work area and the availability of navigational aids would have biased the statistics. For some tasks, driving into the work area and setting up for a manipulation or tooling operation took 10 - 40% of the total task time; in other tasks, such as those in which objects had to be placed into a container, the percentage of time spent driving was higher.

The RWV has mobility characteristics that are well-suited for work in flat floor environments such as production facilities. The RWV has two important capabilities, omni-directional¹ locomotion and multi-mode steering, both of which result from computer coordination of the RWV's four independent steering actuators, each of which provides 180 degrees of motion. The RWV has two modes of driving: *curvilinear* (also called "four-wheel steer" mode) and *translational* (also called "crab" mode). In *curvilinear mode*, the front wheels are steered in a direction parallel to each other and opposite the rear wheels. The steering angle determines the radius of curvature of the driving path which varies from infinity (driving straight ahead) to zero (turning in place). In *translational mode*, all four wheels are steered in parallel and the robot moves along a straight line in the direction that the wheels are pointing. Changing from one mode to the other is accomplished by selecting a steering mode push-button at the console. In all tasks, operators used a mix of translational and curvilinear driving. Lateral translational driving (i.e., directly left and right) was found to be especially useful and was the primary mode used in several tasks, such as following a length of pipe along a wall.

Remote driving of the RWV was found to be more difficult than remote manipulation, as evidenced by operators' preference to use boom, Badger and manipulator motions over driving motions to position tools. In this sense, the base locomotor was used as a mobile platform for gross positioning of the manipulation motions within the workspace. In particular, many operators reported it was rather difficult to return to a particular pose² after driving away (e.g., to deposit an object in a waste drum). Some operators overcame this difficulty by executing simple driving maneuvers that could be easily reversed and/or repeated. The RWV currently does not report heading and distance travelled, information which would have aided the operator for remote driving.

1. Omni-directional locomotion means that the robot can follow any path on a flat surface and assume an arbitrary orientation at any point along that path.

2. Pose means position *and* orientation

Better feedback to the operator can improve remote driving. A difficulty in remotely driving the RWV was judging its proximity to objects in its surroundings. All operators reported that the main cameras provide the most useful perspectives for driving, but the pan and tilt positioning actuators moved too slowly. Operators often used the camera on the manipulator's wrist during driving because it can see the front and sides of the robot and can be rapidly positioned thus providing a means to quickly assess the robot's proximity to obstacles. Conversely, the rear camera, which has a wide field of view ("fish-eye") lens, was found to be the only camera needed for driving backwards. For driving, the 3D graphics display was useful only to indicate the direction in which the wheels were pointing and the orientation of the main cameras. Manipulation

The RWV has appropriate manipulator kinematics for the class of D&D tasks that were attempted. In all tasks, operators were able to achieve the necessary pose of the manipulator to successfully perform the specified operations with the selected end effector. This is not surprising since the manipulator possesses the six degrees of freedom which are required for general positioning in three dimensions with arbitrary roll, pitch and yaw orientation.

Separating manipulator control from the rest of the robot (locomotion and boom) allows straightforward control of end effectors. The manipulator has a self-contained controller system that is independent of the control system that drives the other robot axes. In most manipulation tasks, the two control systems were used independently and sequentially; boom and driving motions were used to first position the manipulator base within the workspace and the manipulator was then operated from that location. In that sense, the locomotor and boom served as a "coarse" positioning system for the manipulator (which has "fine" motions), a scheme that operators were able to learn quickly and use effectively.

The RWV has sufficient dexterity for the class of D&D tasks that were attempted. The operators successfully combined boom motions with manipulator motions to execute all tasks, but favored the manipulator, which is more dexterous. Remote manipulation tasks such as grasping and positioning tools require a great deal of dexterity, since they cannot be pre-planned in enough detail to pre-program a robot to execute them. Instead, operators use finesse to adjust their actions as a task proceeds. In many respects, the remote manipulator is a projection of the operator's arm in the remote working environment. Our operators reported general dissatisfaction with the manipulator master arm noting weaknesses in ergonomic design and excessive friction in its joints that at times limited their ability to control the manipulator effectively.

Position control alone is sufficient for some, but not all D&D tasks. All operators reported that tasks like dropping an object into a container, grasping an object that was free to move (e.g., a section of pipe laying on the floor) and grasping when there was little concern for damaging the object were easy to perform. In contrast, tasks like turning a valve or cutting through a pipe with a saw or grinder were rather difficult. The difference between these two classes of tasks is that the latter require control of both force and position while the former can be successfully accomplished with position control alone. In a similar vein, all operators found the ability to "lock out"³ motion of one or more manipulator axes useful when using the grinder to cut pipes.

3. "Locking out" a manipulator effectively removes one of its degrees of freedom by disconnecting its input on the master arm from the corresponding output on the slave arm such that moving that degree of freedom on the master has no effect on the slave.

Better feedback to the operator can improve remote manipulation. Operators often reported difficulties in judging distances during manipulation tasks. Preferences for camera views varied, but most operators favored the gripper camera most of all and made extensive use of the left and right manipulator cameras. The main cameras were used primarily for set up, then occasionally used during the manipulation task, more for observation than to actually control the manipulator. In some manipulation tasks, operators reported difficulty achieving a desired end effector orientation while avoiding collisions between other parts of the robot and its surroundings. Operators indicated that the 3D display was marginally useful for manipulation; it did provide a way to quickly obtain the current configuration of the boom and manipulator, but lacked context of the robot's workspace and therefore could not help operators to position the end effector or avoid collisions between the manipulator and its surroundings.

5.2 Tooling

Many shelf-available tools can be readily adapted for remote performance of D&D tasks. A simple standardized mechanical interface allowed us to use several tools with both the manipulator and the Badger heavy tool deployment mechanism. The interface consisted of a plate to which the tool was bolted or clamped; a standardized bolt pattern on the tool mounting plate allow it to be mated either to a similar plate on the left or right side of the Badger or to an H-handle for the manipulator gripper to grasp (Figure 3.11). In general, an entire tool mounting procedure took only a few minutes to perform using simple hand tools.

Hydraulic tools are preferred for many D&D tasks. Advantages of hydraulic tools over electric counterparts include higher power densities, higher force/torque output, and more forgiveness in overload conditions. The hydraulic shears and grinder were both found to very effective cutting implements; the performance of electric saw, however, was rather disappointing. The shears were superior for cutting pipes, though grinder was somewhat more versatile (cutting pipe brackets, for example). One drawback of the shears was the need to add a pressure intensifier and related hydraulic components to run at its rated pressure. Both were useful for D&D tasks and, given that the RWV has a hydraulic power supply and spare control valves, were easily adapted for remote operation.

The ability to deploy multiple tools facilitates D&D tasks. In all selected tasks, the RWV carried one or two tools which were installed prior to the test. (One tool was fixed to one side of the Badger and the other was either carried in by the manipulator or placed in a tool "holster" on the other side of the Badger.) Since the tasks performed were limited in scope and known in advance, e.g., cutting pipes and retrieving them, it was possible to outfit the worksystem with tools specifically matched to the task. For real D&D operations, it may not always be possible to select the best two tools before the mission; hence, the worksystem will need to carry a broader range of tools into the workspace.

Operation of many tools requires dexterity and precise manipulator control. Operators reported difficulties in operating the grinder with the manipulator. Holding the line of cut was difficult while also maintaining the proper rate of advance. However, they reported that it was relatively easy to achieve the initial pose before beginning the actual grinding. In contrast, it took more time to position and orient the shears (which were mounted on the Badger because they are too heavy for the manipulator), but once properly located the cutting operation was trivial. The major

difference is that cutting with the grinder requires maintaining position control throughout the entire cut, while cutting with the shears requires position control for initial set up only.

Different modes of manipulator control are needed for different tooling operations. If in addition to master/slave mode, the manipulator were controlled directly by computer, some tooling operations would be easier to perform. This was shown by the difficulties of cutting with the grinder and turning valves in the absence of force control. The RWV manipulator does have teach/playback capability, a control feature that was found useful in paint spraying.

The Badger heavy tool positioning mechanism was a useful addition to the RWV since it allowed use of the shears and provided a mounting location for a tool holster. However, since the Badger lacked a roll motion, what ever tool was attached to it could only operated in a single plane (for example, the shears could only cut horizontal pipes). The Badger's pre-tensioning foot would have been more useful if had an end effector such as a gripper to hold pipes as they were cut or a camera for close observation of tooling operations. Encoding the Badger's motions would also improved its operation, since it could then have then been included in the 3D configuration display and also used in conjunction with the manipulator's teach/playback capability to create an automatic tool changeout routine.

5.3 Operator Interface

The RWV console is well designed for single-operator telerobotic control. All operators reported that the paged menu approach to auxiliary functions was logically designed and easy to use. They reported no difficulties using multifunction joysticks with mode switches to control boom and driving functions. Some operators would have preferred hard controls (e.g., switches and miniature joysticks) for operating tools, though all had positive comments about the footswitch and the use of soft controls on the touchscreen to assign to the footswitch to particular tools. Reported drawbacks were primarily ergonomic issues, the most notable being the location of the touchscreen and the viewing angle of the video monitor. In addition, there was no way to change the vantage point for viewing the 3D simulation of the worksystem configuration.

Operator skill level and experience significantly affects overall performance and efficiency of remote work. The time to execute any particular task varied significantly from operator to operator. Some, but not all, operators were quite adept in all aspects of RWV operation and quickly learned ways to use and combine features and motions to perform remote work. All operators did, however, show improvement as they gained experience with the system, reducing execution times in their second and third attempts at repeated tasks.

5.4 Configuration

Worksystems of RWV scale are appropriate for D&D operations. In the tests conducted, the RWV negotiated hallways and doorways scaled for human access without difficulty. Its tether did not hinder mobility, though are tests did not explore the issues associated with tether management when driving long distances. Despite its compactness, it demonstrated significant reach and lifting capacity. The worksystem was also quite stable even with the boom at full extension due to its low center of gravity. Even though it is rather heavy (weighing over five tons), it was easily transported by a flatbed truck and lifted by our overhead crane. One drawback of the RWV is its

large number of spaces, particularly between exposed hoses and cables, that could collect contaminants.

Use of hydraulic actuation for primary worksystem motions is appropriate. Hydraulic actuation was suitable for all primary RWV motions (driving, steering, boom, manipulator, stifflegs, tether reel, and some tools) since they need to be forceful. Further, given the safety concerns of remote operation the hydraulic system's low speeds were appropriate. The availability of a hydraulic power supply also simplified the addition of tooling and modifications to boom control. The hydraulic system did, however, require substantial maintenance; at one point during the testing program we had to replace seals in most of the actuators and valves, though failure of the original seals is attributable to their age (8 years).

Good system documentation is essential for maintenance, debugging, and worksystem upgrades. Because the RWV is electrohydraulic, it probably required more maintenance than it would have were it all-electric. Maintenance was complicated somewhat by the complexity of the RWV hydraulic system which was designed for redundancy. Fortunately, we had extensive documentation, including detailed design descriptions, parts lists, drawings and schematics, all of which were invaluable in the design and implementation of worksystem enhancements and regular system maintenance.

A real time processing system is essential for mobile worksystem control. Not counting the manipulator (which has its own control system), RWV I has nearly forty controllable motions, many of which have to be coordinated. Controlling this many motions from an offboard location would have required a very large number of conductors between the robot and controller, so placing the controller onboard the robot was warranted. The division of control responsibilities between the onboard computers, which performed all time critical tasks such as closing servo loops and coordinating motions, and the console computer, which converted operator inputs into robot commands, also worked well.

6. Future Work

6.1 Phase 2 Objectives

In Phase 2 of the project, we will conceive, design, build and test a next generation mobile worksystem, the RWV II. This system will be designed using knowledge gained in Phase 1 about DOE's programmatic approach to environmental restoration and waste management as well as conclusions drawn from the testing of the RWV testbed in Phase 1. The primary objectives for Phase 2 are:

- produce a modular robotic system able to perform D&D tasks in real operating scenarios within the DOE complex;
- enhance mobile worksystem effectiveness and productivity through improved operator interfaces and telerobotic controls;
- incorporate and complement technologies developed in other ER&WM programs; and
- improve the knowledge base for performing decontamination and decommissioning operations with telerobotic systems.

The following sections outline our proposed concept for the RWV II.

6.2 RWV II Design

The RWV II design concept is based on tasks that are on or close to human scale. RWV II, like its predecessor, will be a highly capable locomotor that supports a tooling deployment platform to which tools are attached. A significant distinction between RWV I and RWV II is that the latter will be designed for greater modularity to facilitate interchange of power sources, tooling deployment platforms, manipulators, tools and sensors, allowing a wider range of tasks, facilities, and problems to be addressed. This is illustrated in Figure 6.1. In addition, we will integrate sensing capabilities to build a 3D workspace model to assist the operator in understanding the work environment and controlling the worksystem in a supervisory mode.

The cores of a modular system are the power and control busses that link the major elements (or "layers") of the worksystem. The power buss will consist of both hydraulic and electric power; the control buss will include both signals and data (see Figure 6.2). The locomotor, tooling platform and tooling layers will be self-contained by virtue of local actuation, local sensing and local controllers that communicate to other layers. An example showing the tooling layer is illustrated in Figure 6.2. This will permit differently configured layers to be readily interchanged without affecting the rest of the system; for example, a tool platform based on a scissor lift might be substituted for one based on a telescoping boom.

Figure 6.1 Modular RWV II Approach

Figure 6.2 RWV II System Block Diagram

Figure 6.3 RWV II Tool Platform Layer Concept

We intend to adopt the *Generic Intelligent System Controller* (GISC) paradigm as the means to organize and refine the RWV software architecture developed in Phase 1. Since much of the software developed in Phase 1 (see Figure 3.9) can be retained in Phase 2; the RWV II software system will be a modification of the current architecture, as shown in Figure 6.4.

A central element of GISC is the Workspace Modeler, a module that maintains a representation of robot state and state of the world around it. The Workspace Modeler embodies *a priori* information including robot geometry, kinematics, and dynamics; function of tools and end effectors; procedures and constraints for safe operation; global structure of the robot's workspace; as well as status information gathered on-the-fly such as current robot location and configuration of the local workspace. With this information, it is possible to create intelligent robot behavior in which decision making is based on evaluations of the state of the world and the state of the robot.

The Workspace Modeler will be based on a commercial robot simulation and modeling package (TELEGRIP™ by Deneb Robotics, Inc.) that has been adopted for similar applications by several DOE National Labs, possibly complemented by the Interactive Computer Enhanced Remote Viewing System (ICERVS) 3D database being developed under a separate PRDA contract by Mechanical Technologies, Inc. ICERVS is attractive because it uses an object-oriented approach and is thus well suited to D&D work which involves manipulation of objects and operations on structures and surfaces. In general, while implementing this system we will evaluate and employ

all available technologies being researched or already under development within the DOE community including work being done at Oak Ridge National Laboratory, the University of Tennessee, Sandia National Laboratories and Pacific Northwest Laboratories.

We plan to use a scanning laser rangefinder (stereo cameras are a viable alternative) to acquire raw workspace geometric data in the form of range images and call on a human operator to resolve discrepancies. Trained operators are quite good at identifying structures even when viewed through conventional (2D) video systems. Furthermore, the operator can add his understanding of the objects' functions which provides context and semantic meaning.

Figure 6.4 RWV II Software Architecture

The RWV II operator interface will retain the best features of the Phase 1 console supplemented with new functionalities resulting in an improved overall design. All primary functions, such as driving, manipulation and tool control, will be controlled by joysticks, buttons and switches located on the operator panel; controls and functions used less often will be accessible through a touchscreen display.

6.3 Phase 3 Testing

During the discussions at the Robotics Mini-Workshop held at METC, it was suggested that we consider the ramifications of Phase 3 testing in a "hot" facility (i.e., one in which significant radiological contamination is present). These include obtaining the appropriate permits and developing detailed plans for installation and removal of the robot, both of which will involve considerable time and money. Hot testing will also require personnel qualified to work in high rad areas, expensive both in terms of exposure and operating costs. The mechanism for subsequently transferring our technology to EM-30 is not clear, though participation in an Integrated Demonstration is a possibility.

As an alternative, a "warm" demonstration in a DOE facility that has features and equipment representative of highly contaminated facilities but where radiation levels allow human entry without special protection is attractive. The lower contamination levels would make it easier to document and observe the machine operations and in the case of a system failure, allow repair or extraction of the machine more readily. There is also a higher likelihood that the machine could be decontaminated to free-release levels, and subsequently shipped to other areas to perform other tasks or reworked to eliminate any weaknesses identified during the demo. Thus a demo in a "warm" facility could provide more benefit at less cost. To date we have identified two potential facilities which meet our requirements as "warm." One is the Integrated Process Demonstration Facility (IPDF) at Oak Ridge and the other is a small research reactor located in Saxton, PA.

The IPDF is designed to test new techniques for reprocessing spent fuel rods. It consists of pipes, valves, pumps, process tanks and monitoring equipment interconnected throughout a multi-level highbay, similar to many other DOE facilities. Some parts of the facility are slightly contaminated, though most areas are accessible by human workers without protective clothing. The site is particularly attractive because it is adjacent to the Oak Ridge Telerobotics Systems Section. This proximity would allow testing and demonstration of RTDP manipulators, tools, controllers and operator interfaces in conjunction with the RTDP technologies for surgical dismantlement and remote decontamination of equipment.

The Saxton facility is a small research reactor owned by General Public Utilities, a commercial nuclear company. It is located in a containment building that is the only remaining structure in the reactor complex; all of the surrounding buildings have already been decontaminated and dismantled. The facility is currently undergoing surveillance and monitoring and must be checked by inspectors quarterly. It can be entered in street clothes but inspectors must wear protective clothing work in the lower levels. This facility is currently scheduled for D&D in 1995-96, which is consistent with our Phase 3 schedule.

7. Conclusions and Recommendations

We have gained an appreciation for the diversity of D&D tasks planned and proposed to transition many DOE facilities to a state in which they can be reused with unrestricted access. Outright demolition is an unacceptable solution to facility decommissioning due to risk of radioactive release, loss of recyclable material, and introduction of huge volumes of contaminated spoils into the environment. D&D of most facilities is expected to be a controlled *de*-construction that proceeds "inside out" in stages beginning with dismantling, decontamination of equipment and piping, sorting of wastes, size reduction and packaging, and ending with decontamination of the building structure itself.

Given the wide range of tasks that must be executed, the weak structure of the settings in which they are to occur, and the diverse environmental hazards within the DOE, it is unlikely that a single worksystem design can meet all the needs. However, despite a huge D&D agenda, the development of several worksystems, each one specialized to a particular task, cannot be justified at this time due to the lack of experience in D&D operations, the lack of specific regulatory requirements, and the lack of detailed plans for facility transition. The most reasonable way to proceed is, thus, the development of versatile worksystems that are able to handle a variety of tools and perform a wide range of tasks. These worksystems must combine brute force for heavy work with dexterity for fine manipulation; they must be reliable for extended use and adaptable to a range of work conditions and settings.

Equally important to machine designs are the interfaces and telerobotic controllers that allow human operators to make effective use of remote worksystems to execute a broad work agenda, cope with unforeseen circumstances and react to changing situations. Since it is highly probable that D&D scenarios will always require a man-in-the-loop, the utility of the remote equipment will be largely dependent upon how well the man and machine are able to operate as combined system. This ability to work cooperatively will be determined by the fidelity of interfaces between the worksystems and human operators and the extent to which the telerobotic controllers can assume responsibility for safe execution of tasks.

Next generation mobile worksystems should give the DOE a useful tool that can be adapted to the needs of a site and quickly put into practice. Modularity of components, both hardware and software, is essential since task requirements, infrastructures, and operating constraints vary across the complex and will change with time as facilities move toward transition. At this point in time, specific needs for D&D are in many respects poorly defined; regulations and policies are in flux, standards for "how clean is clean?" do not yet exist, and overall strategies for meeting D&D requirements in the face of budget limitations are lacking. Furthermore, experience in prior D&D operations is limited, making it difficult to plan, cost, and schedule the D&D activities that will span the DOE complex for the next two decades.

Likely scenarios for near term use of remote worksystems focus on strategies for taking unused facilities into a phase of surveillance and monitoring in which they will remain until rigorous D&D plans are developed. Surveillance and monitoring can be facilitated by *de-inventorying*, the removal of radioactive material from the area to reduce radiological hazards and requirements for physical security and *de-activation*, decontaminating the area to the lowest level reasonably achievable by cleaning, containing, shielding and eliminating "hot spots" through dismantlement

and highly selective (“surgical”) removal of equipment. These activities will lower the cost of long term surveillance and monitoring by reducing requirements for worker protection.

The “d&d” (for de-inventory and deactivation – as opposed to “D&D” for Decontamination and Decommissioning) scenario has several advantages:

- Component technologies for D&D can be developed, tested and proven in real operations in real facilities.
- Worksystems can be demonstrated on a smaller scale than full D&D activities, allowing expertise and experience to be developed at lower cost and with less risk.
- A knowledge base of cost and time factors associated with remote worksystem operation can be created to help devise long term D&D plans and cost estimates.

There are several technologies currently available or under development that can be advantageously applied to mobile worksystems for D&D. Advanced operator interfaces, sensing, data processing and modeling capabilities for workspace modeling, manipulator control schemes, tools and other relevant technologies are being developed both within and outside of DOE. It is therefore imperative that we stay abreast these development programs and be responsive to the needs of DOE sites as future worksystems are integrated. Specific conclusions and recommendations about D&D worksystem attributes are presented below.

7.1 Mobility

Both the curvilinear and translational steering modes are useful for D&D tasks and worth retaining in the RWV II design. In addition, though not currently implemented, it may be desirable to add a third steering mode in which the robot body rotates about some point along its longitudinal axis, e.g., the end of the boom. It also appears advisable to incorporate navigation and automatic guidance capabilities in the RWV II design. Position information could either be provided to the operator as a navigational indicator or be incorporated into automatic driving controls. Both would assist in maneuvers such as shuttling back and forth between two locations or moving along paths that had been driven previously. Some tasks, such as radiological mapping, will require knowledge of position in a global coordinate frame so that acquired measurements can be related to the locations from which they are collected. There are several mature technologies available for navigation of interior spaces, ranging from dead-reckoning (which works very well on flat floors) to more sophisticated guidance systems based on beacons, to correlation of observed features in the robot’s environment with their known locations on a map.

Though placement of the RWV cameras is adequate for driving, improvements should be made to speed up assessment of clearances. These improvements can be achieved in several ways, including lenses with wider fields of view, faster camera positioning actuators and displaying objects in the robot’s surroundings in the 3D display. The latter will require onboard sensing to measure proximity, but has the potential for providing the fastest means to make clearance assessments since the operator can see the entire surroundings of the robot in a single view. The operator should also have the ability to change his/her vantage point in the simulation to “move around” in the simulated robot workspace. It might be also useful to provide the operator with a

perspective as if he/she were driving onboard the robot. Other RTDP research efforts, including programs at Pacific Northwest, Sandia, Oak Ridge, and Mechanical Technology Inc., have successfully combined range sensing (stereo cameras, laser radar and structured lighting) with a commercial robot simulation package (Deneb Robotics' IGRIP) to create such a display environment. Their results can and should be leveraged to improve mobile worksystem operations.

7.2 Manipulation

Manipulators that are roughly the size of, but substantially stronger than, the human arm are appropriate for remote D&D work. D&D tasks require manipulators that have at least six degrees of freedom; additional worksystem motions are needed to locate the base of the manipulator in the workspace. Since the mobile worksystem has redundant degrees of freedom, a more complex robot controller would be required to coordinate motions of the manipulator with boom and driving motions. Such a controller would seek to optimize the combination of robot motions based on a set of constraints imposed by the current configuration of the robot and its relationship to its surroundings. This additional complexity does not appear to be necessary, however, since worksystem operators can coordinate redundant motions quite effectively. Providing the operator with better information about the configuration of the robot and its relationship to its surroundings would improve his/her ability to coordinate motions safely.

More difficult manipulation tasks can be facilitated by sensing the manipulator's workspace. Information about the manipulator's proximity to objects in its surroundings can be included the 3D display not only to help guide the end effector but to safeguard the rest of the manipulator linkages. The workspace model might also be used as a telerobotic control scheme to automatically generate safe end effector trajectories, allowing the operator to command the end effector pose without concern for collisions. Again, similar efforts in other RTDP programs have shown the viability of such an approach and should be brought to bear on this work.

Performance and efficiency can be improved through more advanced control schemes in which forces at the end effector are measured and fed back to the manipulator control system and/or the operator. Force information can be used in several ways ranging from simple limiting of end effector forces/torques in selected directions to elaborate compliant motion control¹ schemes. The ability to lock out selected manipulator degrees of freedom when operating in master/slave mode is also necessary; it would be useful to extend this scheme by limiting motion of the end effector to specified trajectories.

7.3 Tooling

There is a wide variety of shelf-available tools that can be easily and inexpensively adapted for use with mobile worksystems for remote D&D tasks; hydraulic tools are particularly useful due to their robustness and high force/torque outputs. It would be worthwhile to undertake a program of modifying a much broader set of tools than was used in this effort to gain further experience and to better understand their utility for D&D operations. In particular, tools such as jackhammers, high pressure water jets, CO₂ blasting systems, vacuum systems and sensors for radiological and

1. In general, compliant motion control is used to achieve a desired mechanical stiffness of a manipulator whose end effector is in contact with an object.

other characterization deserve attention. Such a program can probably be executed at a modest expense and should bring together other tool development/modification efforts within the RTDP.

Use of a single standardized tool interface providing mechanical, electrical and hydraulic connections that can be made and broken remotely and automatically would facilitate tool interchange. Tool interchange would permit remote worksystems to carry several tools, thus allowing it address a broader scope of work on a single mission. Given anticipated operating scenarios in which mobile worksystems will perform surgical equipment dismantlement and highly selective decontamination, this approach appears to be preferred over carrying a single tool into the workspace. However, there may be situations in which the latter approach is justified by the volume of work that can be performed with a single tool, e.g., cutting a large number of pipes. Ultimately, the selection and number of tools will be driven by the amount and nature of the work agenda.

Some simple additions to the RWV would simplify the D&D tasks we performed. For example, the task of cutting pipes and placing the cut sections in a container could be performed more readily by adding a mechanism to hold the pipe as it is cut (so that the cut section does not fall to the floor) and by providing the means to carry the container around (so the robot does not have to drive back and forth to the container). A second camera to provide close up views of the end effector would speed set up and improve remote control during tooling operations. The Badger tool deployment mechanism is useful for operating tools too heavy for the manipulator, since operating these tools generally does not require a great deal of dexterity. The Badger's utility could be improved by adding motion encoders and a roll mechanism. Alternatively, a manipulator with larger payload capacity could eliminate the need for the Badger altogether.

7.4 Operator Interface

Because the human operator is essential for effective worksystem operation, the mobile worksystem's operator interface is a critical element of the overall man/machine system. Just as a well designed interface will facilitate remote D&D activities; a poorly designed interface can degrade the performance of an otherwise capable mobile worksystem. Attention to ergonomics and operator comfort is essential to achieving this goal.

The operator interface design should emphasize the aspects of worksystem control that are used most often without comprising access to secondary functions. The approach used in the RWV console of having a small number of reconfigurable hard controls (joysticks and switches) for primary motions and a touchscreen with a menu of soft controls to operate less frequently used functions and to configure the hard controls has worked well.

The interface should also provide rich information about the state of the robot and its workspace without overwhelming the operator. Live video displays need to be positioned for comfortable viewing and should have high resolutions. Robot simulation software driven by real time joint angle measurements can be used to generate a 3D graphical representation of the robot that allows the operator to quickly assess the robot's configuration. This display could have far greater utility by adding representations of the robot's workspace and pan, tilt, zoom and rotate functions for changing the operator's view point in the simulated world.

Incorporation of the new worksystem capabilities and control modes described above will significantly impact the operator interface design. Anticipated changes include additional mode switches for both driving and manipulation, hard controls for tool control and soft controls for initiating automatic sequences such as automatic tool changeout. The robot simulation/workspace model will also require new operator interface capabilities. In particular, we expect a great deal of operator interaction to position sensors and to construct the workspace model itself.

7.5 Configuration

Dexterous, light-duty worksystems of similar scale to the RWV can readily maneuver through settings like DOE weapons production facilities and have the reach perform a wide range of tasks relevant to D&D within them. Increased modularity of design can increase the relevance of mobile worksystems to larger numbers of sites. For example, substituting onboard power generation or storage and wireless communications for the tether will extend the worksystem's operating range and make it possible to operate in settings where tethering is not viable. Likewise, accommodating a wider variety of tools will allow the worksystem to address a broader range of D&D tasks.

Electrohydraulic actuation has significant advantages over all-electric designs for this class of work machine, though the future designs should use a more simplified hydraulic system. Regular maintenance procedures and schedules need to be developed and adhered to in order to ensure long term worksystem reliability. Design for decontamination also needs to be improved.

To effectively control the numerous worksystem motions and monitor its status, the mobile worksystem should have an on-board real time controller. Computer boards compatible with the software and operating system used to develop the RWV controller are presently available with radiation tolerances in excess of 10^6 rad. It is important that the controller measure and report the motion of all joints both for safety and for displaying the robot's configuration in the graphical simulation. Software should also be modularly designed and compatible with other robot controllers so that future upgrades can be made with minimum effort.

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Appendix A - Detailed Worksystem Description

A.1 Locomotor

The RWV's locomotor provides omni-directional mobility that enables maneuvering in congested areas and during work tasks. Four-wheel drive and steering allow turns of any radius while the vehicle is driven in forward or reverse. Lateral translations to the left or right allow threading through constrictions and efficient maneuvering for work along walls. A rocking front axle provides limited suspension for driving over obstacles. Four stifflegs stabilize the vehicle against tip-over during high-reach, high-force tasks.

The locomotor is concentrated in the lower two feet of the RWV. Included in the locomotor is the frame/reservoir which is both the structure of the vehicle and the hydraulic reservoir. Four wheel modules provide vehicle mobility; four stiffleg modules provide additional stability and rigid ground contact for elevated boom and tooling operations.

A.1.1 Structure

The frame, constructed entirely from type 304 stainless steel, consists of a lower base plate, an upper deck, two boom support columns, and many plates interconnecting these elements. The base plate is approximately a 3'W x 8' L plate with cutouts for the wheel modules and motor/pump access ports. The upper deck of the locomotor is attached to the lower deck by a series of 26 vertical plates. The 1" thick boom support columns tie the base plate to the upper deck. These columns exert high forces on the rest of the frame and are, therefore, heavily gusseted and welded.

A.1.2 Propulsion and Steering

The propulsion and steering system has four wheel modules that provide the vehicle's locomotion capabilities. The wheel modules have independent mechanical, power, and control systems so that individual failures do not affect other wheel modules. Each wheel module consists of a steering actuator, a wheel yoke, a wheel motor, and a wheel. Each wheel module can be propelled forward or backwards and can be steered over a range of 180 degrees, allowing locomotion modes such as translation, rotation about the vehicle axis, and articulated curvilinear driving. Steering coordination is effected by computer control of position servos on each of the four steering actuators. The steering angle of each wheel is controlled by a rotary actuator driven through a hydraulic servo valve and its position is controlled using a rotary potentiometer. Wheel rotation is encoded by a Hall effect sensor triggered by magnets mounted on the wheel spaced 6" apart along the circumference.

A.1.3 Stifflegs

Each stiffleg module is composed of a rotary actuator, an extensional actuator, and an interconnected sub-framework (the stiffleg arm). The rotary actuators which have a total rotation of 180 degrees are foot-mounted to the frame of the vehicle at each corner. When stowed, the stifflegs fold against the locomotor frame; when fully extended, the stifflegs swing out horizontally and increase the overall width of the vehicle by approximately 2 feet. The stiffleg arms mount to the output flanges of the rotary actuators and support the hydraulic cylinders that extend downward to contact the floor and ultimately lift the RWV. The rotary actuator plumbing is

affixed to the frame of the vehicle; hydraulic lines for the extensional cylinder are routed through a hydraulic swivel mounted on the axis of the rotary actuator.

A.2 Boom

A.2.1 Structure

The boom's elevation and extension actuators enable the boom to deploy tooling throughout a large work envelope. A tooling platform at the end of the boom supports the manipulator and the Badger heavy tool deployment mechanism. The boom is composed of a main section, supporting boom-mounted hydraulics, and a fly section, telescoping out from within the main section. Hydraulic lines and electrical cabling for boom tip tooling and video cameras are routed in a hose track assembly attached to the boom.

A.2.2 Boom Elevation

The boom elevation actuator is capable of 120 degrees of rotation. The actuator is attached to the boom support columns with twelve 1-inch bolts that thread into the torque and idler flanges of the actuator. The actuator is then connected to the main boom section mount plate through the actuator foot mounts and four 1.5 inch high-strength stainless steel bolts.

All three axes of boom motion (elevation, extension and tooling platform tilt) have position servos. The actuators are driven by proportional valves mounted above the boom elevation actuator and the resulting motions are encoded with potentiometers. The valves contain an internal feedback system that can maintain constant flow rates within 1% of the commanded value. The boom extension sensor is a string potentiometer whose body is mounted on the underside of the boom. Its cable is routed over a pulley into the main boom section and is secured by a bolt to the end of the fly section. The boom elevation sensor is a string potentiometer mounted on a stationary plate slightly below and behind the drum of the elevation actuator. Its cable is pulled below the drum and attached to a second plate mounted to the drum. The tooling platform sensor is a rotary potentiometer that measures the relative angle between the fly section and the tooling platform. The sensor body is fixed to the fly section end by a standard servo potentiometer mount; the shaft is fixed to the platform through a flex coupling. The entire assembly is enclosed to prevent damage from accidental collisions and falling debris. Each potentiometer is configured as a voltage divider whose output is measured by an A/D converter in the on-board controller.

A.2.3 Boom Extension

The main boom is a 9 inch square stainless steel box section, approximately 8 feet long with a wall thickness of 1/4 inch. On one end of the boom main section there is a mounting plate for the elevation actuator; the other end of the main section is the bearing surface on which the fly section travels. Hydraulic components and a video camera are mounted to the top of the boom main section. Also mounted on the top surface of the main section are two valve packs that supply power to boom actuators and other valving and manifolds associated with boom functions. These packs are enclosed by a removable protective cage that is equipped with bump sensors that will stop boom raise motion if a collision occurs, preventing damage to both the boom and the environment.

The fly is an 8 inch square stainless steel box section, approximately 8 feet long. The boom fly section slides into the boom main section and is driven by the extension actuator, a double acting hydraulic cylinder. The forward end of the fly section is a mount for the tooling platform tilt actuator. The fly also supports the hose track assembly and the extension actuator.

The hose track assembly manages the travel of the hydraulic and electrical conductors between the moving tooling platform and the main section. Hoses coming from the rear of the boom first enter the flex track, which is fixed to the boom main section at one end and to the tool platform at the other. The flex track is completely unrolled at full extension of the boom and is doubled over when fully retracted.

The boom extension actuator provides the mechanical force to slide the fly section in and out of the main section. The actuator consists of a carbon steel casing with a stainless steel headcap and piston and is secured by pins at the rear of the main section and at the tip of the fly section. The actuator is positioned inside the boom so that the piston extends with the fly section. Both hydraulic connections to the extension actuator can be made or broken without removing the actuator from the boom.

A.2.4 Tooling Platform

The tooling platform provides a rigid mounting platform for the manipulator and Badger and is the site of outlets for both electric and hydraulic power for tooling. The platform straddles the boom tip rotation actuator with two flanges that bolt to the actuator.

The tooling platform actuator attaches the tooling platform to the end of the fly section and allows the tooling platform to be tilted relative to the boom. The actuator is a foot-mounted pivot actuator mechanically limited to 90 degrees of rotation. It is bolted via its foot mounts to the mount plate of the fly section by four high strength stainless steel bolts. The actuator is positioned so that its rotational axis is parallel to the elevation actuator.

A.3 Tether Management

The tether management system consists of 120 ft. of tether, a reel with integral slip ring pack mounted at the rear the RWV, and a level wind capstan that guides the tether on and off of the reel and prevents entanglement. The reel pays out, retrieves, and stores tether to prevent damage during vehicle motion.

A.3.1 Tether

The tether is a custom-made multi-conductor cable that interconnects the RWV and its off-board Power Distribution Unit. At the core of the tether are two shielded twisted wire pairs (2 x #22 AWG copper with braided shield and hypalon jacket) that are used for ethernet (10BaseT) data communications between on- and off-board computers. The core also contains a 5/16" ID Tygon tube that can be used to supply purge gas to the main electronics enclosure. Surrounding the core are twelve RG-59 coaxial cables (#22 AWG copper center conductor, polypropylene insulation, copper shield and PVC jacket). One of these coaxes is dedicated for manipulator telemetry, seven are used for video, two are used for audio, and two are spares. Layered around the coaxes are 21 #12 AWG copper conductors, of which two are used for AC ground; two each make up separate 120 VAC circuits for the on-board controller/valve power supplies, video system, cooling system

and an auxiliary circuit; three each make up 480 VAC 3Ø circuits for the left motor, right motor and electric tooling; and two are spares. The cable bundle is jacketed with an 1/8" thick black hypalon; the overall diameter of the tether is approximately 1.75".

A.3.2 Reel & Capstan

The reel is a stainless steel drum vertically mounted at the rear of the robot. This drum is grooved so the first wrap of tether seats properly; the second layer wraps in the grooves created by the first. On the left side of the reel is a level wind mechanism that synchronized to move up and down as the drum rotates so the tether is evenly distributed the on the reel. Mounted on this level wind is a capstan with hydraulically motorized rollers that ensure proper tether tension. In the center of the reel is a slip ring pack which passes electrical signals between conductors in the moving tether and conductors affixed to the robot.

A.4 Video and Lighting

There are seven cameras on the RWV, strategically located and positionable to give the operator all the views necessary for safe operation of the robot and observation of work tasks. There are two navigation cameras, three manipulator cameras, one boom-top camera and one rear camera. All cameras on the RWV are color CCD cameras with an 1/2" imaging element, electronic shutter, automatic gain and auto-iris lenses. Each camera is enclosed in a submersible cylindrical housing to which one or two 12V, 50 watt halogen lights are attached. Specifications of the on-board camera modules are presented in Table A.1.

Table A.1 RWV Camera Module Summary

module	actuation	range of motion	lens focal length (adjustment)	# of lights
Manipulator Wrist	none	—	6 mm (manual)	1
Manipulator Left Shoulder	tilt	360°	6 mm (manual)	1
Manipulator Right Shoulder	tilt	360°	6 mm (manual)	1
Left Main	pan & tilt	pan: 170° tilt: 90°	12.5 - 75 mm (remote zoom & focus)	2
Right Main	pan & tilt	pan: 170° tilt: 90°	12.5 - 75 mm (remote zoom & focus)	2
Boom-top	none	—	12 mm (manual)	1
Rear	tilt	360°	3.7 mm (manual)	1

A.4.1 Navigation Cameras

Two navigation cameras, located on either side of the RWV, provide overall perspectives of the space around the robot, help assess clearances, observe stiffleg placement and wheel orientations and monitor tooling operations. Both cameras are mounted on electric pan and tilt mechanisms

that have integral feedback potentiometers that indicate pointing angle and enable the motion of the navigation cameras to be under position servo control. Each camera module has a pair of lights, one on either side of the camera enclosure, and a lens with remote zoom and focus control. The right navigation camera module is mounted above and approximately six inches out from the front of the electronics enclosure and the left navigation camera module's mounted above and approximately six inches out from the front of the hydraulics enclosure.

A.4.2 Manipulator Cameras

There are three manipulator cameras, one on the wrist and one on each side of the manipulator at the shoulder joint. The wrist camera is mounted in a fixed position, focused on the tip of the gripper to provide a close in view of the end effector. The two shoulder cameras provide a wider view of the manipulator workspace and are useful in assessing clearances around the manipulator. Both shoulder cameras are mounted on electric tilt actuators; all lenses on the manipulator cameras have a 6 mm focal length and manual focus adjustment.

A.4.3 Rear & Boom-top Cameras

The rear camera provides a view of the area behind the RWV and allows the operator to observe the tether as it is paid out and reeled in. The rear camera has a wide-angle (3.7 mm) fixed focus lens to allow observation of the rear stifflegs in both stowed and deployed configurations. The rear camera is mounted on a tilt mechanism to allow the operator to observe both the tether reel and the tether that has been paid out behind the RWV.

The boom-top camera is mounted in a fixed position at the rear of the boom main section. It lets the operator assure that there is sufficient clearance to raise the boom. Its lens is a 12 mm manual focus which is focused at approximately the mid-point of the boom main section.

A.5 Hydraulic System

The hydraulic system generates and directs the fluid power that moves the RWV. It controls the flow and pressure of fluid to and from the actuators. The hydraulic system includes a fluid reservoir, two hydraulic pumps, valves, and plumbing. The hydraulic system can be separated into two basic components, the hydraulic power supply and the fluid distribution system.

A.5.1 Hydraulic Power Supply

The RWV hydraulic system is driven by a pair of pressure compensated, variable displacement pumps each of which is driven by a totally enclosed 480 VAC, 3Ø electric motor. The two pumps are plumbed in parallel through check valves to the main distribution valve manifold as shown in Figure A.1. One pump delivers 4.5 gpm at 2000 psi; when the second pump is brought on line, the system pressure is raised to approximately 2400 psi with a total output capacity of 9 gpm.

A.5.2 Distribution Manifold

After the check valve in the hydraulic power supply, the fluid is then routed to a distribution valve pack. The distribution manifold distributes pressurized fluid to and recovers low pressure fluid from 6 valve packs: four directional, one servo and one proportional. The manifold includes eight solenoid valves that can be actuated to block both the pressure and return lines of the output ports. Normal state for these solenoid valves is off (open).

The distribution manifold has a single input port and seven output ports. The seven output ports are then routed to each of the valving manifolds, including: Servo Manifold (steering), directional Manifolds 1 through 3 (locomotor), Manifold 4 (boom), Proportional (boom), and pilot manifold. All manifolds receive pressurized fluid from and returns low pressure fluid to the distribution valve pack.

A.5.3 Direction Valves

Directional manifolds control the flow of fluid to and from the individual actuators, allowing them to be driven in different directions or locked in place. The packs consist of a manifold, eight spring-loaded bi-directional cartridge valves with solenoid actuation, eight needle valves and a lid. Both open-center and closed-center cartridge valves are used on the vehicle, depending on the requirements of the actuator. The closed-center cartridge blocks flow in the center position, and the open-center cartridge allows free flow through in the center position. The cartridge valves are each controlled by independent magnetic solenoids which are powered and controlled from the electronics enclosure.

A.5.4 Proportional Valves

The proportional valve pack includes three Vickers 5 GPM proportional valves with internal spool position feedback. The proportional valves supply bi-directional flow at flow rates proportional to a +10VDC to -10VDC control signal from the electronics enclosure, allowing fine (< 1% spool position error) control of actuator speed. The three actuators operated by the proportional valve pack are the boom raise/lower, boom extend/retract, and boom tip pitch up/down.

A.5.5 Servo Valves

The servo valve pack consists of five Jet-pipe servo valves that control the steering actuator of the four wheels, plus one spare. The servo valves receive control signals from the electronics enclosure and supply constant flow output regardless of supply pressure. The coordination of the four steering actuators is accomplished in the electronics enclosure.

Figure A.1 Hydraulic System Schematic

A.6 Control Console Touchscreens

The touchscreen is used to control all auxiliary functions. The touchscreen is divided into three areas. A status area located at the top of the screen displays the system status and any warning messages. The menu strip located at the bottom of the screen allows direct access to any other screens. The center area has buttons related to the particular screen you are displaying. This section shows the layout of the various screens including: power, drive, tools, video, stifflegs and tether.

A.6.1 Power Screen

The power control screen allows control of the system power start up and shut down. To turn on the hydraulic system the valve power must be enabled along with one or two hydro pumps depending on flow demands. (See Figure A.2 and Table A.2)

Figure A.2 Power Screen

Table A.2 Power Screen Button Functions

Button	Function
Valve power	Switches power to the valve packs
Tool power	Switches electric power to the tooling
Left pump	Turns on and off the left pump
Right pump	Turns on and off the right pump
Spare pump	Switches on and off a spare power supply (430V 3Ø)
E-stop reset	Resets the emergency stop
Unlock	Unlocks the servo loops

A.6.2 Drive Screen

The drive screen displays a bar which can be adjusted to set the top speed of the drive and boom motions. By touching the bar to move the shaded area up or down the top speed is increased or reduced. (See Figure A.2 and Table A.3)

Figure A.3 Drive Screen

Table A.3 Drive Screen Button Functions

Button	Function
Drive	Controls the speed of the boom and drive actuators

A.6.3 Tooling Screen

The tooling control screen controls the onboard tooling. An optional footswitch can also be used to actuate tooling. (See Figure A.4 and Table A.4)

Figure A.4 Tooling Screen

Table A.4 Tool Screen Button Functions

Button	Function
Hydro Rt	Maps the Badger's right tool on/off to the footswitch
Hydro Lf	Maps the Badger's left tool on/off to the footswitch
Hydro Pl	Maps the spare tool port on/off to the footswitch
Elec 1	Maps the electric outlet 1 on/off to the footswitch
Elec 2	Maps the electric outlet 2 on/off to the footswitch
Ext Rt	Extends the badger right tool mount
Ret Rt	Retracts the badger right tool mount
Ext Lf	Extends the badger left tool mount
Ret Lf	Retracts the badger left tool mount
Ext Ft	Extends the badger foot
Ret Ft	Retracts the badger foot
Rot Lf	Rotates the badger to the left
Rot Rt	Rotates the badger to the right
Badger enable	Switches hydro to the badger functions

A.6.4 Video Screen

The video control screen maps the display of the seven video cameras onto the four video displays and their associated fixed controls. (See Figure A.5 and Table A.5)

Figure A.5 Video Screen

Table A.5 Video Screen Button Functions

Button	Function
7 Tether	Maps camera 7 to a monitor position
6 Boom	Maps camera 6 to a monitor position
5 Main R	Maps camera 5 to a monitor position
4 Main L	Maps camera 4 to a monitor position
3 Manp R	Maps camera 3 to a monitor position
2 Manp L	Maps camera 2 to a monitor position
1 Wrist	Maps camera 1 to a monitor position
0 Single	Toggles the quad splitter from single to quad view
1,2,3,4	Monitor position where camera is displayed

A.6.5 Stifflegs Screen

The stiffleg screen allows control and placement of the four stifflegs. (See Figure A.6 and Table A.6)

STIFFLEG CONTROL																								
Deploy All	Out F Rt	Out F Lf	Out R Rt	Out R Lf																				
Stow All	In F Rt	In F Lf	In R Rt	In R Lf																				
Extend All	Ext Fr Rt	Ext Fr Lf	Ext Rr Rt	Ext Rr Lf																				
Retract All	Ret Fr Rt	Ret Fr Lf	Ret Rr Rt	Ret Rr Lf																				
<table border="1" style="width: 100%;"> <tr> <td>POWER</td> <td>DRIVE</td> <td>TOOLS</td> <td>PREFS</td> <td>VIDEO</td> </tr> <tr> <td>DIAG</td> <td>TEACH</td> <td>DEVELOP</td> <td>STIFFLEGS</td> <td>TETHER</td> </tr> <tr> <td colspan="5" style="text-align: right;">SHUTDOWN</td> </tr> </table>										POWER	DRIVE	TOOLS	PREFS	VIDEO	DIAG	TEACH	DEVELOP	STIFFLEGS	TETHER	SHUTDOWN				
POWER	DRIVE	TOOLS	PREFS	VIDEO																				
DIAG	TEACH	DEVELOP	STIFFLEGS	TETHER																				
SHUTDOWN																								

Figure A.6 Stiffleg Screen

Table A.6 Stiffleg Screen Button Functions

Button	Function
Out F Rt	Rotates front right stiffleg out to the side for deployment
In F Rt	Rotates front right stiffleg into the stored position
Ext Fr Rt	Extends the front right stiffleg
Ret Fr Rt	Retracts the front right stiffleg
Out F Lf	Rotates front left stiffleg out to the side for deployment
In F Lf	Rotates front left stiffleg into the stored position
Ext Fr Lf	Extends the front left stiffleg
Ret Fr Lf	Retracts the front left stiffleg
Out R Rt	Rotates rear right stiffleg out to the side for deployment
In R Rt	Rotates rear right stiffleg into the stored position
Ext Rr Rt	Extends the rear right stiffleg
Ret Rr Rt	Retracts the rear right stiffleg
Out R Lf	Rotates rear left stiffleg out to the side for deployment
In R Lf	Rotates rear left stiffleg into the stored position
Ext Rr Lf	Extends the rear left stiffleg
Ret Rr Lf	Retracts the rear left stiffleg
Deploy All	Rotates all the stifflegs out to the side for deployment
Stow All	Rotates all the stifflegs into the stored position
Extend All	Extends all the stifflegs
Retract All	Retracts all the stifflegs

A.6.6 Tether Screen

The tether screen allows control of the tether management system. (See Figure A.7 and Table A.7)

Figure A.7 Tether Screen

Table A.7 Tether Screen Button Functions

Button	Function
Tether In	Takes up the extra tether
Tether Out	Feeds out tether from the take-up reel

Appendix B - RWV Task Evaluation Form

Date_____ Start Time_____

Task_____ Finish Time_____

Video ID_____ Elapsed Time_____

Task Director_____ Operator_____

Task Type -- Open, Schematic, Blind

1. Did you experience any major interruptions or problems in performing this task? How long were you delayed?

2. Describe how you approached this task. What strategy did you use; in what order did you attack the parts of the task?

3. What was the easiest part of this task?

4. What was the most difficult part of this task?

5. What was the most frustrating operation you had to perform? How could the machine or the console have eliminated this frustration?

6. What was the most useful feature? How and why was it useful? (console & machine)

7. Evaluate your approach to this task. What would you change about your strategy if you could perform this task again?

8. Check all functions that you used. Circle the most useful in each category.

Kraft Arm

- Slave Mode. ☐
 Teach/Playback ☐
 Stow/Deploy. ☐
 With Tool 1 _____ ☐
 With Tool 2 _____ ☐

Badger

- Tool 1 _____ ☐
 Tool 2 _____ ☐
 Pre-Tension Foot ☐
 Rotary Joint. ☐

Tools

- Grinder mounted on _____ ☐
 Sheers mounted on _____ ☐
 Sawzall mounted on _____ ☐
 Crowbar mounted on _____ ☐
 Sensor mounted on _____ ☐
 Paint Sprayer mounted on _____ ☐

Boom Coordinated/Joint Motion

- Raise ☐
 Intensifier Raise ☐
 Extend ☐
 Platform Tilt ☐

Stiff Legs

- Manually Deployed ☐
 Automated Deployment ☐

Driving

- High Speed ☐
 Low Speed ☐

Steering

- Crab Mode ☐
 Drive Mode ☐

Tether In/Out. ☐

E-Stop ☐

Cameras

- Wrist ☐
 Left Elbow ☐
 Right Elbow ☐
 Left Nav ☐
 Right Nav ☐
 Boom Top ☐
 Rear ☐

Zoom/Focus

- Left Nav Camera ☐
 Right Nav Camera ☐

Lights

- Wrist ☐
 Left Elbow ☐
 Right Elbow ☐
 Left Nav ☐
 Right Nav ☐
 Boom Top ☐
 Rear ☐

Pan/Tilts

- Left Elbow Tilt ☐
 Right Elbow Tilt ☐
 Left Nav Pan ☐
 Right Nav Pan ☐
 Left Nav Tilt ☐
 RightNav Tilt ☐

Microphones ☐

3D Display ☐

Sensors

- Pressure ☐
 Temp ☐
 Wheel Ticks ☐
 Bump Sensor ☐
 Filter Clog ☐
 Pitch/Roll ☐

DATE

FILMED

7/7/94

END