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Performance Benefits of Telerobotics and Teleoperation

Enhancements for an Arm-Based Tank Waste Retrieval System

D. S. Horschel, P. W. Gibbons, J. V. Draper, E. Grasz, M. Edenburn, S. Thunborg

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Performance Benefits of Telerobotics and Teleoperation
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Enhancements for an Arm-Based Tank Waste Retrieval System

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Abstract

This report evaluates telerobotic and teleoperational arm-based retrieval systems that require advanced robotic controls. These systems will be deployed in waste retrieval activities in Hanford's Single Shell Tanks (SSTs).

The report assumes that arm-based, retrieval systems will combine a teleoperational arm and control system enhanced by a number of advanced and telerobotic controls. The report describes many possible enhancements, spanning the full range of the control spectrum with the potential for technical maturation.

The enhancements considered present a variety of choices and factors including:

- the enhancements to be included in the actual control system,
- safety,
- detailed task analyses,
- human factors,
- cost-benefit ratios, and
- availability and maturity of technology.

Because the actual system will be designed by an offsite vendor, the procurement specifications must have the flexibility to allow bidders to propose a broad range of ideas, yet build in enough restrictions to filter out infeasible and undesirable approaches. At the same time they must allow selection of a technically promising proposal.

Based on a preliminary analysis of the waste retrieval task, and considering factors such as operator limitations and the current state of robotics technology, the authors recommend a set of enhancements that will

(1) allow the system to complete its waste retrieval mission, and
(2) enable future upgrades in response to changing mission needs and technological advances.

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Executive Summary

In December 1991 the Department of Energy adopted the position that retrieval and disposal of the waste in all the Single Shelled Storage Tanks (SSTs) would become the planning basis for the Tank Waste Retrieval Storage (TWRS) Program. The Tri-Party Agreement (TPA) stipulates that the removal process be demonstrated on an actual tank. This report evaluates teleoperational (human-directed) and telerobotic (computer-directed) control system features that could be used in an arm-based waste retrieval system to be deployed in Hanford's SSTs.

The development of the waste retrieval system is planned to occur in two, or more, stages. A first generation arm will be developed to retrieve waste from a set of relatively simple tanks. Waste in the remaining, more complex, tanks may be retrieved by enhanced production systems.

The procurement specification for the first generation arm must have the flexibility to allow bidders to propose a broad range of ideas, yet build in enough restrictions to filter out infeasible and undesirable approaches. Selection of a technically promising proposal needs to be allowed. Potential vendors will receive results from technology development studies, such as this document, as part of the bid package. This information should help vendors to prepare proposal packages with fewer risks and unknowns, and, therefore, provide more competitive bids.

Tank C-106 at Hanford will provide experience for ongoing retrieval efforts. A first generation arm should have at least a limited capability in advanced robotic control system features. Additional production systems are expected to include extended capabilities in those areas. Robotics experience gained from operation of the first generation system can, therefore, guide choices for later systems.

It should be emphasized that certain technological "enhancements" can be implemented independently of any other advanced technology. However, some enhancements cannot be implemented unless the system already includes the prerequisite robotic features. Even equipped with these prerequisite features, a system can normally be used for simple teleoperation. Otherwise, extensive hardware and software changes may be required to provide the feedback control mechanisms, strength, and dynamic response needed to convert a simple teleoperated manipulator into a robot.

Typical challenges facing the retrieval systems include recovery of hard salt-cake wastes and removal and disposal of in-tank hardware. Reliable and timely control of the retrieval system is demanded by the following factors:

- the size and complexity of the tanks,
- the safety implications of their chemical and radiological hazards, and
- an aggressive retrieval schedule.

The level of control chosen will depend of the specific tasks required and the availability of mature, reliable control system features. The following synopsis presents in short form the available options.

Synopsis of Options

Teleoperation vs. Telerobotics

As a foundation for this report, it is important to understand the distinctions between a teleoperational system and a telerobotic system. This distinction will allow comparison of capabilities and enhancements and a comprehension of how the two control approaches can work in tandem to accomplish the retrieval of tank waste.

Teleoperation (Human-Directed)

A teleoperational system extends an operator's sensing and manipulating capabilities to a remote location. The system includes the means to artificially sense the remote environment, to move the manipulator, and to communicate between the operator and the manipulator. The operator controls all of the manipulator's movements by moving an input device which is tracked by the manipulator. These systems have a direct mechanical connection between the input device and the manipulator.

Teleoperated systems can be further divided into "mechanical systems" and "truly remote" systems. In a truly remote system, the manipulator and the input device are physically separated, and a computer forces them to track via electrical signals. The control system considered in this report is a truly remote system.

Because the operator of a teleoperational system is intimately associated with the motions of the manipulator, system performance is influenced by the quality and types of feedback available to the operator. Numerous feedback channels can improve operator performance. Three types of feedback are commonly used. In order of preference they are :

- visual feedback facilitated by direct viewing through a lead-glass window, or by remote video cameras.

- bilateral force reflection that allows the operator to "feel" physical contact on the manipulator through a corresponding resistance to motion by the input device.
- monitoring sound in the remote location also provides clues that an operator can interpret.

Successful application requires that system designers must consider human factors such as operator limitations, inaccuracies, and fatigue, especially for long periods of operation or repetitive tasks.

Telerobotic (Computer-Directed)

A robot, in a general sense, is a machine that uses sensors and computational capabilities that allow it to respond to functional commands, rather than simply tracking the motions of an input device. A robot can learn sequences of operations, then repeat these operations as instructed by the human operator. Typical "teach and repeat" operations include the following:

- defining points in the work space,
- defining paths between points,
- opening or closing a gripper,
- changing tools, and
- completing higher level tasks.

Using sensors and proper control programs, the robot can also react to and interact with its environment. Essentially, the human is no longer required to input every move, instead, he or she supervises the operations at some level of control.

The term, telerobotic, refers to programming and using a robot from a distance or a remote location. Even though the operator of a telerobotic system generally uses the information at a higher level of control, many of the sensory feedback issues discussed for teleoperation also apply to telerobotics. Because a robot may still be used as part of a teleoperated system, it is beneficial to include similar appropriate feedback channels to the operator, such as vision, forces, and sound.

Levels of Control

The relative merits of teleoperation vs. robotics must be considered in the context of a continuum ranging from pure manual control to pure robotics. System designers must select, from the technology available, the level of control best suited for efficient and safe performance of the waste retrieval operations. The issue involves assigning the proper mix of decision making between the human and the computer, and ascertaining where decisions are most reliably and safely made. For example, a computer may be best able to plan paths to avoid collisions, whereas a human may be best at selecting the destination position. In one sense, the desired level of control is different for each task. An ideal system could respond to the demands of a particular task and provide a level of control appropriate to each task or sub-task.

Control Requirements

The fundamental function of the arm control system is to position an End Effector (EE) where it can dislodge and mobilize waste, while preventing damage to the tank and retrieval equipment. This section expands this general requirement into sub-functions and requirements that are relevant to selection of the robotic level of control.

Control System Functions

The control system must provide methods to determine and visualize the in-tank configuration of the waste and In-Tank Hardware (ITH), so that retrieval operations can be planned. During operation, the operator should have continuous oversight of the activities and be able to intervene in the case of unforeseen challenges and/or safety concerns. Displays must allow the operator to "see" the arm or a model of it and the EE relative to the in-tank configuration.

The control system must provide the operator with adequate controls to achieve an aggressive retrieval rate currently targeted as 30 gal/min. during active operation. Assuming a continuous process, a relatively uniform motion of the EE over the waste surface is required while maintaining the proper standoff distance for the dislodging and mobilization functions. In addition, the arm and/or conveyance system must be controlled to avoid plugging, while adequately picking up the dislodged material and any added water.

Control System Requirements

Protection of Tank and Retrieval Systems

The arm and EE must not damage the tank during operation. In addition, the arm and EE must not damage themselves or other parts of the retrieval system. The most successful way to protect the tank is to prevent contact, and/or limit the forces, with which the arm contacts the tank, liner, risers, and equipment inserted through the risers, and to provide the control system with enough knowledge of its deployed configuration to prevent impacts with itself. Motions or activities that could damage the robot, its end effectors or other equipment, such as impact loading, high accelerations, contacting unknown buried objects, or plugging of the conveyance line must also be avoided.

Operator Effectiveness

The system must be operable by suitably trained Hanford operations personnel. Human factors considerations that suggest automation of highly repetitive and intense operations will avoid operator fatigue and resultant errors. The system should provide the first line of defense against mishaps and limit the consequences of operator errors.

Accommodation of Different Waste Types

The system must accommodate a variety of waste types, which have been described as salt-cake, sludge, and/or liquid. To achieve target retrieval rates for each type of waste, it will be necessary to adjust speed, standoff distance, and other control parameters. Methods are needed for the operator to evaluate retrieval performance and make the appropriate adjustments.

Update from In-Tank Changes

The control system must be able to accommodate changes in the in-tank configuration of both the waste surface and ITH. Methods are needed to keep the control and protective features updated and operational as the in-tank features move or are exposed during the retrieval process.

Fault Recovery

The control system must provide sufficient notification and status information for safe, effective fault recovery. It must also be designed so that no single failure (including an operator error) can result in an unacceptable safety, or operational, consequence. Maintaining integrity of the tank is one of the functions that must be able to accommodate a single mode failure.

Upgradability

The control system should be designed to be readily modifiable, and/or upgradable, including the capability for the future addition of new control system features. Because this project builds a first generation system, changes to control and mining algorithms are likely to be needed through the system's operational life. Anticipating this evolution establishes a primary reason for building a first generation system. To ensure a good return on the investment, the changes should be added to the first generation system and proven before additional systems are ordered.

System Configuration

This report assumes that the first generation arm-based retrieval system will consist of a teleoperational arm and control system enhanced by a number of advanced and telerobotic controls. The report describes many possible enhancements, spanning the full range of the control spectrum and a range of technical maturity.

A basic teleoperated system is considered as a convenient "reference system" for consideration of enhancements. Specific features of such a system are described below.

Based on a preliminary analysis of the waste retrieval task, and considering factors such as operator limitations and the current state of robotics technology, the authors recommend a set of enhancements defining a "Minimal System" that will:

- allow the system to complete the waste retrieval mission, and
- enable future upgrades in response to changing mission needs and technological developments.

Specific features of the "Minimal System" are presented in the "Recommendations" section at the end of this summary.

The potential enhancements present a variety of choices. It is likely that several combinations could successfully complete the waste retrieval mission. In selecting the enhancements to be included in the "minimal" control system, designers must consider many factors, including safety, detailed task analysis, human factors, cost-benefit ratios, and availability/maturity of technology.

Teleoperational Configuration

This report constructs a convenient referral case for consideration of potential enhancements. The system described will not necessarily meet all of the previously discussed requirements. It is a basic teleoperational (manually controlled) system that relies on manual control from the operator and has no supervisory control functionality. It has the following features:

- End-Point Controlled Teleoperation — Nominal computer control allows the operator to move the end-point directly, without having to control each joint individually.

- Constant Human Control — The operator directly controls all manipulator motions via the input device. Operator perception and performance are a primary factor in the performance and safety of the system.

- Video Camera Inspection/Observation — Cameras provide the visual information to allow the operator to assess and control the retrieval operations.

- Confined Sluicing Hydraulic EE with Air Conveyance — The system is assumed to use a high pressure hydraulic EE that, in laboratory studies, needs precise standoff distances of approximately 1 inch +/- 1/2 inch from the waste surface to achieve optimal performance.

Note that such a system would probably not be inherently capable of incorporating many of the supervisory control enhancements recommended for the minimal waste retrieval system; however, if these control enhancements were incorporated, the system could still be teleoperated as before. Thus, the sensors and system responsiveness which enable robotic control are "enabling enhancements" for all other enhancements.

This reference system is also not necessarily acceptable for deployment, because it may not meet all the requirements. The requirements for a minimum deployable system are primarily driven by the needs of the EE and conveyance system as well as by specific safety constraints, which are not firmly established at this point. Testing of the reference water-jet technology for waste mobilization is on-going, but initial indications are that the positioning and motion requirements for efficient EE operation will be difficult to achieve in the (reference) teleoperational mode. Manual operation of a robot of this size, with the visibility limitations expected in the tank, under these operational requirements would be extremely demanding of operator skill and concentration.

Control System Enhancements

The enhancements described in this report have the potential to improve safety and efficiency of operations and/or reduce the demands on the human operators of the manipulator. Detailed descriptions of specific enhancement technologies and their relative advantages are contained in Section 4 of this document. The descriptions in Section 4 include references to current literature and operational experience for each of the technologies.

Enhancements represent a range of technologies and levels of control, from improvements on the traditional teleoperated manipulator to the introduction of telerobotic controls. There are many reasons that the first generation system should be not only "robotics capable," but also include a number of the proven enhancements. Most importantly, it is expected that without benefit of several key enhancements, the reference teleoperational system described in this document will, at best, have difficulty meeting all of the operational requirements. In addition, the robotic enhancements are expected to pay for themselves in terms of increased retrieval rates versus numbers of systems required.

To meet long-term program objectives, the first generation arm-based retrieval system should be both versatile and extendible. In particular, the system should be capable of being controlled telerobotically as well as teleoperationally. The particular features used in the control system design will be a function of the chosen system design and the proposed mining strategy; however, certain enabling features, which ensure that the system is robotically controllable, are so important that they should also be required.

Recommendations

The teleoperational (only) system is limited to a single control paradigm, and cannot accept many of the automatic control or robotic enhancements discussed. A robotics-capable system, however, provides the flexibility and extensibility required to protect the initial investment by facilitating adjustment to emerging requirements and allowing the use of maturing technology. For example:

- Design adjustments need to respond to late-breaking changes in requirements and discoveries during the retrieval process.
- Unforeseen problems may arise with the chosen control scheme which would be less costly to correct if a "toolbox" of robotic enhancements could be applied.
- The first generation system is the precursor to the follow-on retrieval systems that will be used in completing the program and should provide knowledge and experience that can be applied toward the advanced features that will be required.

Recommended enhancements to this teleoperational control system are presented in this section and further discussed in Section 4. A "minimal system" is defined by listing enhancements to the teleoperational (only) system that the authors believe are necessary for a successful retrieval system. Other enhancements could be included when they are appropriate to a chosen design approach.

Minimal System

A minimum system should include both teleoperational and telerobotic capabilities The recommended minimal system does go beyond the system discussed because some features have been deemed necessary to successfully meet the retrieval, operational, and safety goals envisioned for the most effective system. Many of these recommended technologies lean toward the ability of the system to be programmable and work with other subsystems in an integrated fashion. They also tend to make the system more versatile. Both features are considered to be extremely important in this first of a kind system.

The overarching technology is an open architecture supervisory control system, because it allows this versatility and expandability and it is required for many of the additional supporting technology enhancements. It is an enabling technology, which can take on various subsets of the other described enhancements, increasing the level of automation. The supervisory control and open architecture of the controller reduces risk by allowing future technology enhancements to be integrated into the system as necessary to complete retrieval or as desirable to enhance performance. The following readily available, proven features should be included:

- <u>End-Point Control</u> (See Section 4.1.1)

End-point-controlled systems allow the human operator to control the movements of the arm's end effector, rather than specifying movements of individual joints. End-point control is a mature technology that significantly improves controllability of the manipulator and is routinely employed in commercially available telemanipulators. This capability is included in the teleoperational system described in Section 2.3.

- <u>Accuracy and Responsiveness</u> (See Sections 4.1.1, 4.1.4, and 4.2.5)

Responsiveness, as described here, is the ability of a manipulator to reproduce the input device's trajectories in time and space and its impedance. The optimal machine accepts forces or movements and converts them to acceleration/position without modifying or constraining the input. Accuracy and responsiveness are measured by several key parameters: position control, velocity control, and acceleration.

The accuracy of the manipulator system needs to be sufficient to allow contact operations with the tank, risers, and waste. With a regulatory requirement to remove 99% of the waste, a heel of less than half an inch is all that would be allowed to remain on the cylinder walls and floor in the cleaning of a full tank. Further, the candidate hydraulic EEs require a positional accuracy of less than an inch. This requirement dictates that the minimal system must have accuracy and repeatability of less than an inch.

As described in Section 4.1.4, Responsiveness, it is preferable for the system to be user-paced, which dictates a desirable acceleration bandwidth above 9 Hz. The constraints of the physical manipulator geometry, such as those imposed by the riser diameter for insertion of the manipulator, may force some compromises on the acceleration bandwidth. A high bandwidth is most desirable.

Sufficient accuracy and responsiveness of the manipulator are important for both teleoperation and telerobotic control. Many of the technologies described below, such as teach and repeat, collision limiting, and force feedback, for example, require that the robot system be accurate and responsive.

- Ability to Allow Future Addition of Any Telerobotic Enhancements (See Section 4.2.5)

Many commercial vendors are working to enhance their current control capabilities. These vendors are pursuing flexible and versatile open architecture control platforms, with multimode control and real-time monitoring of internal and external environments. This practice points out the need to be able to incorporate new technology as it becomes available.

By its modular and expandable nature, a robotic system with supervisory control provides the best posture for enhancement and is necessary for reduction of risks associated with the arm-based retrieval system. The supervisory control and open architecture of controllers reduces risks by allowing future technology enhancements to be integrated into the system as necessary to complete retrieval, or when desirable, to enhance performance.

- Operator Visualization Suitable to Implement the Selected Mining Strategy, Likely to Include Enhanced Video Imaging or Graphical World Modeling (See Sections 4.2.2 and 4.3.1)

Graphics-based simulation systems allow the operator to manipulate a graphical representation of the manipulator and modify intended movements before they are executed by the manipulator. This type of programming allows a robot to be programmed more rapidly and safely than if programmed by line-by-line coding or trial-and-error.

Accurate graphical modeling requires advanced vision and sensing capabilities to provide an accurate image of the tank interior. Primary emphasis is on volumetric representation, obtained by *a priori* engineering data and geometric sensors. This area has been rich for recent technology advances and is reflected in a variety of available sensors. Graphical based programming and a means to update the robot's graphical world model as the robot alters its environment are recommended.

- Force Feedback or at Least a Visual Display of Forces (See Section 4.1.2)

Force feedback is an important supplementary sensory channel. It can be provided in a number of ways. Extensive research has identified advantages and disadvantages for implementation of, and reliance on, each method. Visual displays of force offer an inexpensive implementation of force feedback, but are often difficult to interpret and may increase the demands on the operator.

Force based control will reduce the risk of damaging retrieval equipment and the tank itself. The minimal system should be capable of sensing and displaying tool tip forces.

- Teach and Repeat Capability for Programming of Routine Operations (See Section 4.2.1)

The ability to program repetitive tasks ensures safer, faster operation and greatly reduces the demands on the human operator. "Teach and repeat" capabilities can be implemented through low-level or supervisory control, using the same user interface and the same input device as the reference teleoperated system, with the addition of a terminal or teach pendant to record points, paths, or programs. It is unlikely that a system lacking this capability can meet the performance requirements of the waste retrieval task.

- Collision Limiting, Including the Forces that can be Applied by a Collision (See Section 4.3.3)

The forces generated by impact or collision of the manipulator hardware with the tank, in-tank hardware, or with other parts of the arm or manipulator itself may be limited or prevented by several means. The arm can be equipped with joint limits, to prevent extension into the tank surface, or with velocity limits to limit the maximum force generated. Either of these methods also limits the performance of the manipulator, resulting in undesirable trade-offs in performance. Joint limits are impractical for accommodating the variety of obstructions imposed by in-tank hardware. More advanced collision avoidance systems may employ sensor capabilities (e.g., sonar, ultrasound, or proximity sensors) to inform the control system of changes in the tank environment, and to respond accordingly. Model based collision avoidance that uses the physical geometries of the robot system and tank environment can be effectively used for obstacle avoidance of known (i.e. modeled) objects.

Model based obstacle avoidance is recommended for the minimal system. This plan will ensure that the robot system does not impact modeled objects in the environment. Using model based collision avoidance also allows remediation action to occur before contact with the obstacle. For example, the robot system could be slowed down as it approaches an object in the workcell. Unknown objects in the environment will need to be avoided by using sensor based methods. This method is recommended for the minimal system; however, it should be noted that performance of the sensor in the tank environment and the relationship between arm performance (the distance it takes and arm to stop, for example) and range of the sensor must be considered during design.

Additional Features that May be Required

Depending upon the system design, waste mining strategy, and other operational considerations, additional features may be necessary to provide a fully functional system with appropriate safety features. While not fully mature, the enhancements described below represent significant potential gains and could be developed with minimal risk of failure. Some of the enhancements which could be added to a "robotics capable" system are:

- Force Reflection (See Section 4.1.2)

Force reflection, a form of force feedback (see above), is a commercially available technology (albeit on smaller robots and manipulators) that enhances the operator's ability to perform complex teleoperational tasks, particularly those involving control of forces. The greatest advantages of force reflection are realized when manual task components require guidance or delicacy in areas that are difficult to see with remote television cameras, or when viewing is hampered by dust, gases, or other obstructions. Force reflection can be applied to the whole arm or just critical joints depending on the application. For example, tool tip force reflection would require sensors only in the wrist area.

The option of force reflection appears to be desirable, but may need to be investigated further to determine the true cost/benefit. Other options such as model based (virtual) force reflection should also be considered and have an inherent advantage over sensor based force reflection of not requiring joint force-torque sensors. The use of model based force reflection seems to be an appropriate means of reflecting important forces back to the operator and should be pursued as this technology becomes more widely available.

- Graphical Programming with Model Update (See Section 4.2.2)

Graphical programming allows the operator to observe collisions and lock out hazardous motions through simulation *before* issuing commands to the manipulator. Graphical programming can contribute significantly to the safety and speed of robotic operations and is recommended, especially as it appears that this technology is becoming increasing available through commercial sources.

- Sensor Based Control (See Section 4.2.3)

The robot's world model as described above can be extremely useful when non-contact operations are performed. When contact of the robot with the environment (including operations that require a precise standoff distance from the surface) is required, the geometric models are not precise enough for these contact operations. The inaccuracies of the world model can be compensated by sensors. It is envisioned that the robot will need to interact with the environment during the retrieval tasks and sensor will need to be used for the precise control of the robot system.

- Increasing Telepresence through Sensor-Based Operation (See Sections 4.3.2.1 and 4.3.2.2)

A key objective of incorporating sensory information is to give the human operator the maximum information about the remote environment. High-fidelity information displays and control outputs relate directly to increases in operator performance and should be incorporated whenever practical. New and emerging technologies that increase telepresence are a thriving area in many industries (not just robotics). It is very likely that advances on these fronts will continue to have a favorable impact on increasing the operator's telepresence and thus performance.

- End-Point Video Tracking (See Section 4.3.1.4)

Real-time visual tracking of robotic motion, or automatically aiming cameras at the tool work location, using commercially available hardware is easily achievable. Automated tracking using remote cameras frees the human operator from this time-consuming task, and allows the operator to concentrate on teleoperation of the manipulator. Since a supervisory controller should not be limited in the type or number of components it can control, coordination of visual tracking with robot position is a natural extension of the advanced control systems. This option is recommended and should be a function of the supervisory control system.

- Stereoscopic Vision (Robotic capability is not required.) (See Section 4.3.1)

Because it provides more visual information to the operator, stereoscopic vision is believed to offer advantages over mono-image television. The precise relationship between stereoscopic vision and performance has not been quantified. Although stereoscopic viewing may not improve overall task completion time, it is likely to increase safety by increasing the ability of the operator to accurately position the manipulator when operating in manual control and may also reduce operator fatigue.

Features not Recommended for this System

The following technologies are either too immature, or do not seem to have significant benefit for the retrieval task.

- Touch/Tactile Sensing

This method of sensing attempts to correlate kinesthetic sensation to patterns of environment or objects in the manipulator's work environment. Such devices require complex arrays of sensors to allow the operator to recognize objects or their orientation in an unstructured, constantly changing environment such as a waste tank.

- Fully Automatic Autonomous Control

This level of control is at the extreme end of the control continuum and would require significant advances in artificial intelligence to be of practical benefit. In the near term, this alternative does not seem practical for the retrieval system.

Performance Benefits of Telerobotics and Teleoperation

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Enhancements for an Arm-Based Tank Waste Retrieval System

1.0 INTRODUCTION

This report compares human-directed (teleoperational) with computer-directed (telerobotic) control system features that could be used in a single-shell tank, arm-based, waste retrieval system such as those found at Hanford.

The development of the waste retrieval system is planned to occur in two, or more, stages. A first generation arm will be developed to retrieve waste from a set of relatively simple tanks. Waste in the remaining, more complex, tanks may be retrieved by enhanced production systems.

The procurement specification for the first generation arm must have the flexibility to allow bidders to propose a broad range of ideas, yet build in enough restrictions to filter out infeasible and undesirable approaches. Selection of a technically promising proposal needs to be allowed. Potential vendors will receive results from technology development studies, such as this document, as part of the bid package. This information should help vendors to prepare proposal packages with fewer risks and unknowns, and, therefore, provide more competitive bids.

The first generation arm will serve as a concept demonstration, and will provide experience for selecting the features of production systems. Therefore, the first generation arm should not be based on a unique or limited concept that will have no bearing on future systems. Because the production arm-based retrieval systems are expected to include advanced robotic control system features, the first generation system should have at least a limited capability in those areas, or an option to upgrade. Robotics experience gained from operation of the first generation system can guide choices for later systems.

The Department of Energy (DOE) Robotics Technology Development Program (RTDP), in the Office of Technology Development, has funded research, development, and first generation applications of robotics technology for waste site remediation within the DOE complex. This research is the primary basis for this report, although technology developed outside the efforts of the DOE has also been included.

This report presents various control system features in the context of potential enhancements to a reference teleoperational system. The merits and maturity of each feature are discussed, with probable impacts on productivity and safety. A scoping analysis is also included to examine the initial cost and life cycle costs of the enhancements. No distinction is made between first generation and production needs, because the ultimate goal is a fully functional system.

Terminology and operating philosophy relating to robotic and teleoperational controls are presented later in this section. Hanford-specific requirements are reflected in the basic control system functions and requirements in Section 2.0. The reference teleoperated system is described in Section 2.3.

Section 3.0 discusses a formal analysis of retrieval tasks. This analysis was conducted to better understand the task of retrieving the waste using either a teleoperated or telerobotic manipulator, and it produces task lists that can be used to estimate the time needed for each motion. This type of analysis can be used to determine where an enhancement could increase system performance.

Section 4.0 describes potential enhancements to the reference teleoperational system. The specific benefits of each enhancement can be assessed qualitatively (i.e., faster, safer, or cheaper) as they relate to the tasks that the arm-based retrieval system must perform. Many of the enhancements have been developed and demonstrated within the RTDP, and some are already employed in the commercial sector. Section 5.0 describes the costs/benefits of the enhancements from a top level perspective. Rather than attempt to define the cost of each feature, the analysis focuses on the overall advantage of a faster and safer system. Conclusions and recommendations are presented in Section 6.0.

It should be stressed that increments in technology are possible. That is, certain enhancements can be implemented independently of any other enhancements; however some of the enhancements require that the system include certain robotic features. A robot can usually be adapted to perform teleoperated tasks. Extensive hardware and software changes may be required, however, to convert a simple teleoperated manipulator into a computer controlled programmable device (i.e. a robot).

1.1 Overview of Tank Retrieval

In December 1991 the DOE adopted a position that retrieval and disposal of the waste in all the SSTs would become the planning basis for the TWRS Program. An agreement (known as the Tri-Party Agreement) between the Washington State Department of Ecology, the Environmental Protection Agency, and the DOE stipulates that the removal process be demonstrated on an actual tank. The first tank to be cleaned will be tank C-106.

Several features make retrieval of waste from tank C-106 less challenging than certain other tanks, and, therefore, attractive for the demonstration. Tank C-106 has been characterized as containing a single waste type (hard sludge) and is relatively free of in-tank hardware that would obstruct retrieval operations. It also is half the depth of the largest 75-ft-diameter tanks. These conditions greatly simplify system deployment and limit the number of tasks the arm-based retrieval system must perform.

A commercial vendor will design and fabricate the retrieval system. Potential vendors will receive the results from the technology development studies, such as this document, as part of the bid package. This additional information should help vendors prepare proposal packages with fewer risks and unknowns, and therefore, provide more competitive bids.

The remaining retrieval milestones of the Tri-Party Agreement address the retrieval efforts necessary to close the 149 single-shell tanks. Enhanced retrieval systems with greater capabilities and greater flexibility than the first generation system will be needed to recover wastes from the larger and more complex single-shell tanks. Typical challenges facing the production retrieval systems include recovery of hard salt-cake wastes and removal and disposal of in-tank hardware.

The Hanford waste-storage tanks range in size up to 75 ft in diameter and contain up to 1 million gallons of waste each. The wastes are chemically and radiologically hazardous. Radiation levels range from slightly above background to thousands of rads/hour, making it necessary to maintain the integrity of the tank shells in order to minimize the potential for release of hazardous material to the atmosphere. The consistency of the waste ranges from pumpable liquids and slurries to thick sludges and large crystalline masses that can be as hard as concrete. Access into the tanks is typically limited to existing risers, but a new riser located in the center of the tank domes is planned for arm-based retrieval systems. Since the tanks are below grade, the retrieval system will have to descend 10-15 ft through the risers to reach the top of the tank. Total distance from grade level to the bottoms of the tanks ranges from 37-50 ft, depending on tank capacity. Some of the tank domes may not support the weight of the retrieval equipment and may require external bracing and supports during operations.

The size and complexity of the tanks, the safety implications of their chemical and radiological hazards, and an aggressive retrieval schedule demand both reliable and timely control of the retrieval system. The level of control chosen will depend on the specific tasks at hand and the availability of mature, reliable control system features.

1.2 Levels of Control

As a foundation for this report, it is important to understand the distinctions between a teleoperational system and a telerobotic system. This understanding will allow comparison of capabilities and enhancements. To clarify the distinctions between teleoperation and telerobotics, four separate comparisons are presented, each from a different perspective. The first is definitions with discussion. The second refers to a "level of control continuum." The third uses pilot control of an aircraft as an analogy. Finally, the application of supervisory control features to an arm-based tank waste retrieval system is discussed.

1.2.1 Definitions

A teleoperational system extends a person's sensing and manipulating capabilities to a remote location. The system includes means for artificially sensing the remote environment, moving the manipulator, and communicating between the operator and the manipulator. The operator controls all of the manipulator's movements by moving an input device which is tracked by the manipulator. Teleoperated systems can be further divided into "mechanical systems" and "remote" systems. For a remote system, the input device and the manipulator are physically separated, and a computer forces them to track via electrical signals. This type of remote system is considered in this report.

Because the operator of a teleoperational system is intimately associated with the motions of the manipulator, system performance is influenced by the quality and types of feedback available to the operator in addition to the operator's skill. Many feedback channels may improve operator performance as long as the operator is not overwhelmed by the information. The most useful form of operator feedback, essential for teleoperational control, is provided by visual feedback — either direct viewing through a lead-glass window or by remote video cameras. Bilateral force reflection allows the operator to "feel" physical contact on the manipulator through a corresponding resistance to motion by the input device. Monitoring sound in the remote location also provides clues that an operator can interpret. For successful application, operator limitations, inaccuracies, and fatigue must be considered, especially for long periods of operation or repetitive tasks.

A robot, in a general sense, is a machine with sensors and computational capabilities that allow it to respond to functional commands, rather than simply tracking the motions of an input device. A robot can learn sequences of operations, then repeat these operations as instructed by the human operator. Typical "teach and repeat" operations include defining points in the work space, defining paths between points, opening or closing a gripper, and changing tools. With sensors and proper control programs, the robot can also react to and interact with its environment. Essentially, the human is no longer required to input every move, but rather supervises the operations at the appropriate level.

The term, telerobotic, refers to human control of a robot at a distance as opposed local control which might be used in a factory. Many of the sensory feedback issues discussed for teleoperation also apply to telerobotics, even though the operator of a telerobotic system generally uses the information at a higher level of control. Since a robot may still be used as a teleoperated system, it is beneficial to include the appropriate vision and force feedback.

1.2.2 Level of Control Continuum

The relative merits of teleoperation vs. robotics must be considered in the context of a continuum ranging from pure manual control to pure robotics. System designers must select, from the technology available, the level of control best suited for efficient and safe performance of the waste retrieval operations. The issue involves assigning the proper mix of decision making between the human and the computer, and ascertaining where decisions are most reliably and safely made. For example, a computer may be best able to plan paths to avoid collisions, whereas a human may be best at selecting the destination position. In one sense, the desired level of control is different for each task. An ideal system could respond to the demands of a particular task and provide a level of control appropriate to each task or sub-task.

Figure 1 shows the level of control continuum. Key control methods are marked at relative points on the continuum. The key control methods are somewhat arbitrary, and the exact placement of each may be debatable, but they serve to illustrate the concepts.

The solid line represents the level of control continuum stretching from pure teleoperation to pure robotics. Boxes to the left of the solid line describe various key control methods or types of control. The ovals to the right of the line categorize the three main regions of the continuum: "Manual Control," "Supervisory Control," and "Robotics Operations." An example of "Manual Control" is a mechanical input device/manipulator used in hot cells. An example of "Robotic Operation" is a welding robot used on an automobile assembly line.

As the level of control shifts toward pure robotics (following the continuum from top to bottom) three conditions emerge:

1. Decision-making is increasingly the responsibility of the machine.

2. Controls and displays are increasingly informational rather than representational.

3. Human inputs are increasingly symbolic.

At the level of "Manual Control," the machine makes no decisions. System controls allow the operator to control the position of an end-effector in space. Displays must provide a representative image of the remote area. Human inputs result in direct manipulation of end-effector position and orientation.

Further down the continuum, within the level of supervisory control, the machine shares in decision making.[1] For example, at the control method of "Manual Control" with automated trajectory guidance, the machine may decide where the end-effector will be in space, based on control inputs and task requirements. The operator maintains some control over the end effector's position. The displays are representative or show progress along the specified trajectory. Human inputs are indirect manipulations of end-effector position and orientation (for example, the operator may control progress along the path but not actual position).

Progressing down the continuum, but still within the scope of "Supervisory Control," at the control method of "Tactical Inputs to Symbolic Interface," the machine accepts commands from the operator and is responsible for executing them. This is "classical" or highly developed supervisory control and, depending on the sophistication, approaches Robotic Operations. The machine decides how to move in order to complete tasks, based on high-level tactical inputs from the operator. Controls are symbolic; that is, they operate at the level of instructing the machine to complete a task, rather than at the level of directly controlling end-effector position. The displays are also symbolic rather than representational. They show icons rather than images. Human inputs are commands. The operator instructs the machine to "do this" or "get the other" and the machine does the actual fetching.

At the pure robotic end of the continuum, all planning, decision making, and operations are machine directed. The human operator assumes a management role.

The location of a system on the control continuum is based on the control method that is currently in use, regardless of system capability. A system that has the capability to run automatically could be setup to be directed manually. Task analysis and available technology will drive the selection of appropriate controls for each type of task.

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[1]Supervisory control, in the context of this report, should not be confused with supervisory control as defined by Sheridan (1992), which is in a strict definition limited to programming or teaching robots.

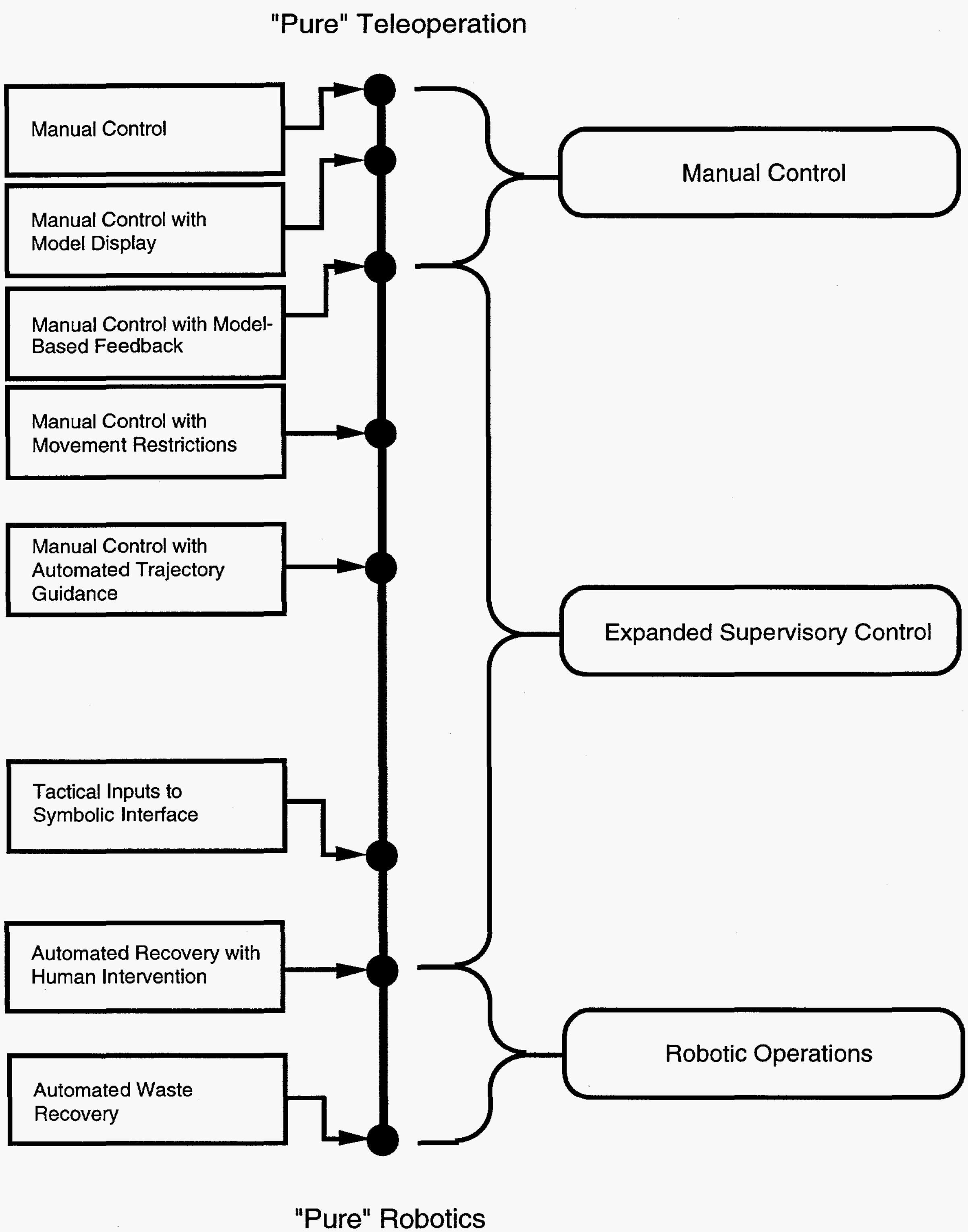

Figure 1. Level of Control Continuum

1.2.3 Contrasting Levels of Control: The Airplane Analogy

It is useful to further contrast "Manual Control," "Supervisory Control," and "Automated Control" using the airplane and pilot analogy.

In "Manual Control" all motions of the system are dependent upon a human in the control loop. Every motion depends on the operator; if the human does not move, the system does not move. A simple system to illustrate manual control is a light aircraft such as a Piper Cub, where all control surfaces are physically connected to the control yoke and pedals by cables. The operator must move the yoke and pedals for the control surfaces to move. The baseline teleoperated system described in Section 2.3 is manually controlled, although a limited computer acts as the interface between the two sides, directing the arm end-point to respond to control yoke position while computing the arm angles and rotations needed to make the move.

In "Supervisory Control" a computer is in the control loop, so that the human acts as the supervisor to the system. Extending the aircraft analogy can illustrate this concept also. The X-29, with its distinctive forward-swept wings, is inherently unstable and requires a computer for stability augmentation to stay airborne. But when the pilot moves the yoke, the aircraft must respond accordingly, which responses are defined as handling qualities. So while the computer interfaces with the pilot to react to the pilot's commands, it must also interact with the airframe through sensors to keep the aircraft stable and airborne. In essence, the aircraft has been turned into a servo system that provides the desired performance. In fact, the system could be described as a teleoperated system that has computer augmentation.

"Automated Control" takes the human out of the loop. The system will perform its task requiring no (and even ignoring) operator input. Again, this can be illustrated with an aircraft analogy. Modern commercial aircraft can be programmed to fly to a specific destination. By using sensors, such as those to read heading and air speed, the aircraft can fly itself to a pre-programmed destination. This auto-pilot must be turned off or overridden for the pilot to regain control over the aircraft. Full automatic control in this analogy, would be an aircraft that could perform all operations, take off, fly, and land without any human intervention.

The computers are used in each stage of control to relieve some of the burden on the human operator. The three categories described here are commonly subdivided, as shown in Figure 1. Sheridan (1992), for example, lists five categories of human function during supervisory control.

1.2.4 Application of Supervisory Control to an Arm-Based Retrieval System

Some real-world examples may further elucidate the distinction between manual and supervisory control capabilities. This section contrasts the two modes using examples of actual arm-based retrieval systems. These examples are only for the purpose of explaining the modes of control and are not intended as recommendations.

1.2.4 a End-Point Control

The reference teleoperational system uses computer control, but only to translate operator motions into a form that the manipulator can follow. This technique is **not** supervisory control, and the system is still classified as teleoperational. The computer does, however, provide end-point control, which allows the operator to command the manipulator by conceptually moving the end-point only, rather than having to move each joint of the manipulator individually.

End-point control greatly simplifies the control over a manipulator and is much more natural for the operator, especially for a redundant manipulator (with more that 6 degrees of freedom) where several possible arm arrangements would position the end-point of the arm at the same place. End-point control allows the operator to think about where the arm end point should move rather than what joints need to be moved to get to a specific position. The computer uses the kinematics (geometry of the robot components and how the components interact) of the arm to transform the desired Cartesian (X-Y-Z) motion into required joint motions. This example illustrates the concept that the computer in the loop can simplify use of a system.

The teleoperational system described in Section 2.3 is a manual control system with end-point control. Every move of the system must be directed by the operator. The following paragraphs seek to further define a supervisory system by contrasting it with a manual system for specific situations or tasks.

1.2.4 b Supervisory Control

Supervisory control goes beyond end-point control to achieve additional advantages. Supervisory control allows several subsystems--robots, sensors systems, conveyance systems, tracking systems, etc.--to be operated from a single point of control in a coordinated manner. This integration and overseeing capability of a supervisory control system allows additional functionality that goes beyond a single robot system.

- *Path Planning* — With a manual control system, the operator uses visual (video) displays to mentally plan a path. The path must stay within the robot's control envelope (joint-limits and other preset parameters) while avoiding potential obstacles. The operator must rely only on training and experience, and the plan cannot be tested without driving the real machine. An incorrect path may be revealed during the drive, sometimes *after* the undesired operations have been performed. In contrast, a graphical-based supervisory system can simulate the robot's path to predetermine its correctness. Only when the path has been approved by the operator does the control system actually move the machine along the path. During the drive, the operator monitors progress and interrupts if necessary. An automatic path planner can be used to ensure that joint, or Cartesian, limits are not exceeded, or to calculate difficult moves and guarantee success if a solution exists, rather than relying on an operator to perform a difficult move by trial an error. Such path planning is generally delegated as a task for the supervisory control system.

- *Tool Changeout* — With a manual control system, the operator moves the manipulator along a path to and from the changeout station as described above, as well as performing explicitly all the actions for disconnecting and reconnecting the end-effector. Each time a tool is changed, the operator performs the exact same operations and is subject to the same risks, such as incorrect paths or skipped steps and misalignment of the tool to the manipulator. By contrast, a system using a supervisory control scheme could be taught the proper location and steps for changeout. The operator would need only to specify the desired end-effector and monitor the operation. The control system would automatically change the end-effector using the information previously established.

- *Waste Dislodging* — With a manual control system, the operator must directly control the placement of the end-effector relative to the waste surface. If the waste elevation changes, the input device must be moved accordingly to avoid digging into the waste or getting too far away for operation. The operator must rely mainly on vision (video) to evaluate performance, even if the camera placement is poor or visibility is limited. By contrast, a supervisory system can be taught, or programmed, to move over the contours of the waste at discrete depth intervals such that the waste is "machined" in layers. Alternatively, proximity sensors could be included to allow the supervisory system to actively control the spacing relative to the waste surface. In either case, the operator would specify the desired large-scale motion and monitor the resultant drive, possibly even adjusting the "elevation setpoint" as the drive progresses.

- *Camera Control* — In a purely manual system, the operator would have to reposition the cameras to provide the best view of the operation. With supervisory control, the cameras could automatically track the end-effector.

- *Dynamic Control* — With a manual control system, the operator must control any oscillatory tendencies of the system. The natural frequency of the arm is likely to be in the region where sudden motions by the operator could cause significant oscillatory motions of the manipulator. Combined with dynamic excitation from the end-effector, keeping the arm steady may be quite challenging. Steadying the arm represents a constant challenge in addition to the operation that is being performed. By contrast, a supervisory control system can be taught to recognize conditions that cause oscillation in the arm and control the arm to counteract or avoid these conditions, so that the operator need not be concerned.

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2.0 BASELINE CONTROL REQUIREMENTS

The fundamental function of the arm control system is to position an end effector (EE) where it can dislodge and mobilize waste, while preventing damage to the tank and retrieval equipment. This section expands this general requirement into sub-functions and requirements that are relevant to selection of the robotic level of control. Because the first generation system is designated as a demonstration unit, the control system should provide the flexibility to adjust the control algorithms and to evaluate entirely new control schemes that will evolve or be developed as a result of the demonstration.

2.1 Control System Functions

2.1.1 Planning of Operational Steps

The control system must provide methods to determine and visualize the in-tank configuration of the waste and in-tank hardware (ITH), so the retrieval operations can be planned. An effective planning capability prevents repeated reliance upon protective safety limits and generally improves efficiency. The range of activities includes:

- Deployment into the tank,
- Simple moves from one part of the tank to another,
- Developing a mining strategy to avoid interfering ITH,
- Planning moves to remove waste, and
- Accommodating changes in the in-tank configuration.

2.1.2 Operational Monitoring

During operation, the operator should have continuous oversight of the activities and be able to intervene in the case of unforeseen problems and/or safety issues. Displays must allow the operator to "see" the arm or a model of it and the EE relative to the in-tank configuration.

2.1.3 Retrieval Rate

The control system must provide the operator with adequate controls to achieve an aggressive retrieval rate currently targeted as 30 gal/min. during active operation. Assuming a continuous process, a relatively uniform motion of the EE over the waste surface is required while maintaining the proper standoff distance for the dislodging and mobilization functions. In addition, the arm and/or conveyance system must be controlled to avoid plugging, while adequately picking up the dislodged material and any added water.

2.1.4 Conveyance Pickup

The arm and/or conveyance system must be controlled for optimum performance. For example, if an end effector, consisting of an hydraulic scarifier and an air conveyance system is used, dependent control of these two subsystems is important. If the pickup shroud is too far from the waste surface the retrieval efficiency drops, and excessive water could be left in the tank. On the other hand, dislodging too much material or getting too close to the waste surface will tend to overload the conveyance system, and could cause plugging. Large variations in conveyance performance will decrease the retrieval throughput and may be detrimental to the system.

2.2 Control System Requirements

High level performance requirements are enumerated in the following sections so that an appropriate minimal system can be defined. Note that the minimal system may necessitate a level of control, or features, that go beyond those of the system that is described in Section 2.3, Teleoperational Requirements.

2.2.1 Protection of Tank and Retrieval Systems

The arm and EE must not damage the tank during operation. In addition, the arm and EE must not damage themselves or other parts of the retrieval system. The most successful way to protect the tank is to prevent contact, and/or limit the forces, with which the arm contacts the tank, liner, risers, and equipment inserted through the risers, and to provide the control system with enough knowledge of its deployed configuration to prevent impacts with itself. Motions or activities that could damage the robot, its end effectors or other equipment, such as impact loading, high accelerations, contacting unknown buried objects, or plugging of the conveyance line must also be avoided.

2.2.2 Articulated Arm Protection

For an articulated arm, precautions assume that the control system has enough information about its deployed configuration to prevent impacts with itself, either by control or design. In addition, contact with the tank, or in-tank, structures must be controlled to prevent damage to the arm.

2.2.3 Operator Effectiveness

The system must be operable by suitably trained Hanford operations personnel. Human factors considerations suggest that highly repetitive and intense operations should be automated to avoid operator fatigue and resulting errors. The system should provide the first line of defense against mishaps and limit the consequences of operator errors. For example, at a shift change, the incoming operator must be able to easily ascertain the status of the system and continue a partially completed operational sequence.

2.2.4 Accommodation of Different Waste Types

The system must accommodate the various waste types, which have been described as salt-cake, sludge, or liquid. To achieve target retrieval rates in each type of waste, it will be necessary to adjust speed, standoff distance, or other control parameters. Methods are needed for the operator to evaluate the retrieval performance and make appropriate adjustments.

2.2.5 Update from In-Tank Changes

The control system must be able to accommodate changes in the in-tank configuration of both the waste surface and ITH. Methods are needed to keep the control and protective features updated and operational as the in-tank features move or are exposed during the retrieval process.

2.2.6 Fault Recovery

The control system must provide sufficient notification and status information for safe, effective fault recovery. It must also be designed so that no single failure (including an operator error) can result in an unacceptable safety or operational consequence. Maintaining the integrity of the tank is one of the functions that must be able to accommodate a single mode failure.

2.2.7 Upgradability

The control system should be designed to be readily modifiable and/or upgradable, including the capability for the future addition of new control system features. Because this project builds a first generation system, changes to control and mining algorithms are likely to be needed through the system's operational life. Anticipating this evolution establishes a primary reason for building a first generation system. To ensure a good return on the investment, the changes should be added to the first generation system and proven before additional systems are ordered.

2.3 System Configuration

This report assumes that the first generation arm-based retrieval system will consist of a teleoperational arm and control system enhanced by a number of advanced and telerobotic controls. The report describes many possible enhancements, spanning the full range of the control spectrum and a range of technical maturity.

A basic teleoperated system is considered as a convenient "reference system" for consideration of enhancements. Specific features of this teleoperational system are described below.

Based on a preliminary analysis of the waste retrieval task, and considering factors such as operator limitations and the current state of robotics technology, the authors recommend a set of enhancements defining a "Minimal System" that will:

- allow the system to complete its waste retrieval mission, and
- enable future upgrades in response to changing mission needs and technological advances.

Specific features of the "Minimal System" are presented in the "Recommendations" section at the end of this summary.

The potential enhancements present a variety of choices and factors including:
- the enhancements to be included in the actual control system,
- safety,
- detailed task analyses,
- human factors,
- cost-benefit ratios, and
- availability and maturity of technology.

Using the high level performance requirements described in 2.2.1 to 2.2.7, a reference teleoperational configuration was assumed. The "reference system" described here serves as a convenient case for evaluation of potential enhancements. It should be stressed that the reference system will not necessarily meet all of the previously discussed requirements, instead it serves as a basis for comparison and discussion.

For the purposes of this study, the reference system will be considered as a basic teleoperational (manually controlled) system, that relies on manual control from the operator and has no supervisory control functionality. It has the following features:

- End-Point Controlled Teleoperation — Nominal computer control allows the operator to move the end-point or end effector directly, without having to control each joint individually.

- Constant Human Control Required — The operator directly controls all motions via the input device manipulator. Operator perception and performance are a primary factor in the performance and safety of the system.

- Video Camera Inspection/Observation — Cameras provide the visual information to allow the operator to assess and control the retrieval operations.

- Confined Sluicing Hydraulic EE with Air Conveyance — The system is assumed to use a high pressure hydraulic EE that, in laboratory studies, needs precise standoff distances of approximately 1 inch +/- 1/2 inch from the waste surface to achieve optimal performance.

Note that such a system would probably not be inherently capable of incorporating many of the supervisory control enhancements recommended for the minimal waste retrieval system; however, if these control enhancements were incorporated, the system could still be teleoperated as before. Thus, the sensors and system responsiveness that enable robotic control are "enabling enhancements" for all other enhancements.

This reference system is also not necessarily acceptable for deployment, because it may not meet all the requirements. The requirements for a minimum deployable system are primarily driven by the needs of the EE and conveyance system as well as by specific safety constraints, which are not firmly established at this point. Testing of the reference water-jet technology for waste retrieval EEs is on-going, but initial indications are that the positioning and motion requirements for efficient EE operation will be difficult to achieve in the reference teleoperational mode. Manual operation of a robot of this size, with the visibility limitations probable in the tank, under these operational requirements would be, at best, extremely demanding of operator skill and concentration.

The following subsections explore the ability of the reference system to meet the requirements previously identified. This background information will help to put into perspective the potential enhancements which will be discussed in later sections.

2.3.1 End Effector Requirements

Several EE have been investigated for the retrieval of waste from the Hanford tanks. A probable candidate EE is based on a high-pressure water jet technology that dislodges the waste and mobilizes it into the inlet of the conveyance system. This EE is used in this study because it has several merits and has had several parametric studies conducted that have resulted in quantitative data that are essential to understanding the impact of the EE on the remote deployment system.

Two parameters influence the effectiveness of the EE: (1) traverse speed, which directly affects the waste cutting depth, and (2) the standoff distance, or distance between the EE and waste surface. Several factors are involved:

1. Larger cutting depths tend to dislodge larger pieces which (at some point) are too large for the conveyance system. Subsequent size reduction is not as efficient because the pieces tend to move around.

2. Cutting and dislodging performance degrades as the standoff distance increases. Current EE testing uses standoff distances of less than 1 in. and efficient waste dislodging appears reasonable at 1 inch from extrapolation.

3. Retrieval of the water used in the cutting operation becomes more difficult as the standoff distance increases.

4. A small standoff distance is difficult to control manually, especially with a variable waste surface.

Current testing data indicate that a reasonable compromise may be achieved with a standoff distance of about an inch and a cutting depth of about an inch. The retrieval strategy resulting from these needs involves many consecutive passes over a surface at about 1 - in. elevation intervals.

Uniform speed control also becomes important, especially for retrieval of salt cake, which requires the EE to cut the waste into pieces. If the EE moves too quickly, the pieces will be too large for the conveyance system and will be left in the tank until a later pass. If it moves too slowly, the retrieval rate will not be acceptable. Thus, for most effective operation, a near optimum motion is needed.

A quick scoping calculation helps clarify the resulting control requirements. A representative EE head could be about 15 inches in diameter. To retrieve 30 gal/min. (115 in^3/sec), with a 1-in. cutting depth, this EE would have to be moved over the surface at about 7-1/2 in/sec.

For a strictly teleoperational system, the operator would be required to move the robot uniformly at 7-1/2 in/sec while keeping the EE 1 in. above the waste surface. Clearly, the operator would require excellent visibility of the EE and waste. Still, this requirement is intense and stringent on the operator, and it may not be achievable without supervisory control assistance.

This conjecture about the EE is not fully agreed upon and will need further investigation. To achieve reasonable teleoperational control, the control problem must be simplified by an order of magnitude. A simple improvement of a factor of two, achieved by doubling the head size or the cutting depth will not mitigate the problem. Such a change would create additional problems, while still leaving a significant control burden on the operator.

This document addresses robotic enhancements that can be added to the reference teleoperational configuration to aid the operator in controlling the arm and the EE. These requirements provide a reasonable basis for consideration of the merit of the robotic enhancements.

2.3.2 Functional Compliance

This section discusses the ability of the reference teleoperational system to meet the functional requirements that are provided in Section 2.1.

A simple teleoperational system would not necessarily include the interfaces necessary to add the robotic control enhancements to the first generation arm system. Hence, to achieve this functionality, some telerobotic features need to be added to the reference system to allow incorporation and testing of the enhancements.

2.3.2 a Planning Steps

With simple teleoperation (visual feedback only), the operator will require considerable training and experience to be able to interpret the TV images and understand the relationship of the arm, EE, tank internals, and waste surface. Cameras will have a limited number of positions and will probably be positioned poorly for some operations and/or regions of the tank. Planning of activities are likely to degenerate to a trial-and-error process with skilled operators eventually being able to visualize and effectively plan operations in their minds.

2.3.2 b Operational Monitoring

As with the planning process, the limited camera viewpoints will restrict the operator's visibility and performance. Also, the operator could easily become so involved in one area (EE position) that another issue (collision of the arm with ITH) is overlooked.

2.3.2 c Retrieval Rate

As previously discussed, the ability to teleoperate the system to achieve the desired retrieval rate is questionable.

2.3.2 d Conveyance Pickup

As previously discussed, effective pickup of the dislodged material will vary depending upon the operator's skill.

2.3.3 Requirements Compliance

This section discusses the ability of the reference teleoperational system to meet the system requirements as provided in Section 2.2.

2.3.3 a Tank Protection

Simple teleoperational control would probably rely on force sensors in the arm to limit applied forces. At speeds of 7-1/2 in/sec, the control system would need to be quite fast and/or the hardware quite compliant in order to detect the loads and shutdown the system before exceeding the load limit.

Reducing travel speeds of the arm would make protection easier, but as previously discussed, this reduction affects the ability to achieve the required retrieval rates. Slower speeds also decrease production by increasing the time to move from one part of the tank to another.

Limiting the load that the system can exert to a few thousand pounds would probably be achievable, but whether this limit will protect the tank adequately is unknown. It is also probable that operator errors (or limitations) will cause this protective feature to be exercised more frequently with teleoperational control than with robot control.

2.3.3 b Self-Protection

Kinematic design, or the low-level controller, should be able to protect the robot from itself. The EE and vulnerable arm sections must be designed to accommodate loads similar to the above tank limits.

2.3.3 c Operator Training

As previously discussed, operators will undergo considerable training to achieve the desired proficiency. Because the operators will control each detail of the motion, the training must impart a broad awareness of the entire system and the interdependencies of the subsystems.

2.3.3 d Differing Waste Types

Limited camera viewpoints would cause the operator's view of the waste surface at the retrieval interface to be highly variable; however, a special camera could be mounted on the arm for close-up viewing of the retrieval interface. With good viewing the operator can probably assess the overall effectiveness of the retrieval better than a computer; however, a computer would be more adept at making the necessary adjustments to keep the entire system within operating ranges.

2.3.3 e In-Tank Changes

Viewing systems would display changes in the tank as they occur.

2.3.3 f Single Failure Criteria

For a teleoperational system, a backup system for tank protection is not apparent, other than a secondary load-limiting system. Perhaps joint limits could be employed to limit extension and prevent contact with the tank liner, but this feature would not prevent contact with ITH. A classic backup system would include model-based collision avoidance, one of the enhancements discussed in Section 4.0. A teleoperational system, without preplanning capability, is also highly prone to "single-mode failures" from operator errors.

2.3.3 g Upgradability

A strictly teleoperational system may not be capable of robotic enhancements. If there is any intention of ever adding any of the enhancements, the needed system responsiveness and control system interfaces must be included from the beginning.

2.3.4 Summary of Reference System Performance

As discussed in the previous subsections, there are serious concerns about the capability of a strictly teleoperational system to meet the functions and requirements of the retrieval system. Subsequent sections of this document will discuss how the level-of-control options influence specific task plans, and will explore a number of potential enhancements that can improve the system controllability of the teleoperational system. A "minimal system" that the authors believe meets all the high level performance requirements is described in Section 6.0.

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3.0 MANIPULATOR TASKS

Control system requirements for a Tank Waste Retrieval Manipulator System (TWRMS) will be driven by the operational and sensing needs of the end effectors and the safe deployment of the retrieval system as a whole. Two factors will determine whether an automated or manual positioning system is appropriate: the effectiveness of the waste form mapping or work area display system, and a practical ability to achieve the standoff distances required for the waste retrieval end effectors to operate efficiently.

It is essential to look next at the projected waste removal tasks, and then evaluate the ability of the reference teleoperational system to complete those tasks. This section looks in greater detail at specific tasks the manipulator could be expected to perform. It proposes a baseline mining strategy for waste removal operations, introduces typical task analysis diagrams and nomenclature, and identifies points that require decisions regarding level of control. Based on the nature of the task, analysis can provide a rationale for why certain levels of control may be appropriate.

This section describes a task sequence analysis that was performed, then details two representative tasks to show the use of the process.

3.1 Task Sequence Analysis

The purpose of a Task Sequence Analysis is to evaluate the effectiveness of an approach in performing a task. The analysis consists of three steps:

1. Identify options for performing tasks.
2. Describe the tasks to be performed.
3. Evaluate the options in the context of the tasks.

A work flow analysis of the tank waste retrieval process has been performed (Draper 1993b) and will not be repeated here. The following sections will use parts of this work flow analysis to illustrate key points. The remainder of this section describes the terminology and process of the work flow analysis.

The retrieval effort for one tank is termed a "mission." A mission includes key milestones that must be accomplished, and these milestones delineate mission phases. Each mission phase includes one or more functions. Each function contains one or more sub-functions. Each sub-function has three elements:

- Initiator — the event or condition that requires or allows the sub-function,

- Task sequence — the sequential list of tasks that operators must complete, and the
- Sequence terminator — the event or condition that is the goal of the sub-function.

The three divisions are also tasks. A task is a set of behaviors executed to fulfill a goal-directed strategy. The task sequence is a set of tasks carried out to fulfill the goal of the sub-function. Tasks are composed of task elements, which are human behaviors required to complete the task.

The following narrative lists the mission phases and the sub-functions within mission phases. For each sub-function, the initiator is listed, followed by a sequential list of tasks required, and the terminator for the sub-function. There are three mission phases during a TWRMS waste retrieval campaign:

1. Insert TWRMS Equipment into the Tank. This mission phase starts with the completion of the above ground facilities needed for waste removal and ends when the TWRMS is in place in the tank and ready to begin waste retrieval.

2. Remove Waste Layers. This mission phase starts at the end of the first phase and ends when all retrievable waste has been removed from the tank.

3. Remove TWRMS Equipment from the Tank. This mission phase starts at the end of the second phase and ends when the TWRMS has been removed from the tank.

This discussion assumes that the primary mission is the retrieval of a waste heel from a typical Hanford single-shell tank. The second mission phase is the critical part of the waste retrieval campaign. The tasks most useful for illustrating the merits of teleoperation and automation occur during this phase. During the second mission phase, risers, in-tank hardware (ITH), and waste are removed in an iterative process. The mission phase starts with the complete TWRMS system operational inside the tank and it ends with all the risers, ITH, and waste removed from the tank.

3.2 Task Analysis Example: Cut Risers/ITH

Although the only risers in tank C-106 are adjacent to the cylindrical tank wall, and the risers are not slated for removal during the waste retrieval efforts, most of the other Hanford tanks contain pipes and other ITH that will need to be removed during remediation. Since cutting and removing pipes is a relatively straightforward process, it allows differences between teleoperation and telerobotics to be contrasted.

The use of sensor-based control for the robotic cutting was demonstrated during the November 1992 Hanford Retrieval Demonstration. The use of sensors for the control of the robot and the mission is considered important to many aspects of tank remediation. The sub-function of cutting risers serves as an example of the use of sensor-based control.

This sub-function is executed repeatedly until all risers and ITH are cut into manageable segments and down to the level of the existing waste layer. Figure 2 illustrates this task, and Figures 3 through 6 illustrate the task sequence. The figures show two possible options for the cutting procedure.

In both cases, operations start by mapping the waste surface to indicate the positions of the risers and ITH. In later robotic operations, the map will provide the user with the necessary symbolic display, or world model of the tank interior. In later manual operations, the map will provide a planning tool and secondary display.

After mapping, the user must decide whether to proceed manually or robotically. If manual control is selected, the user moves the end effector to the next ITH, places the end effector on the ITH, and begins cutting. If robotic control is selected, the user must first select the ITH to be cut by indicating the pieces individually or in a series. The user can then preview the sequence by replaying it on a graphic world model developed from mapping and *a priori* engineering data. When satisfied, the user can initiate the robotic cutting sequence. During robotic cutting, the user watches the world model and television display to monitor progress and to detect faults. The user may override the robotic routine to re-teach or assume manual control. As was demonstrated in the 1992 Hanford Retrieval Demonstration, a precise world model is not required because the contact operation of the cutter with the pipe is a sensor based operation.

The initiator for this sub-function is *TWRMS operational in tank.* The terminator for the sub-function is *Risers/ITH cut into manageable sections.* This sub-function and the supporting tasks of *Map Surface, Manual Cut, Teach Cut,* and *Robotic Cut* are graphically represented in Figures 2 through 6.

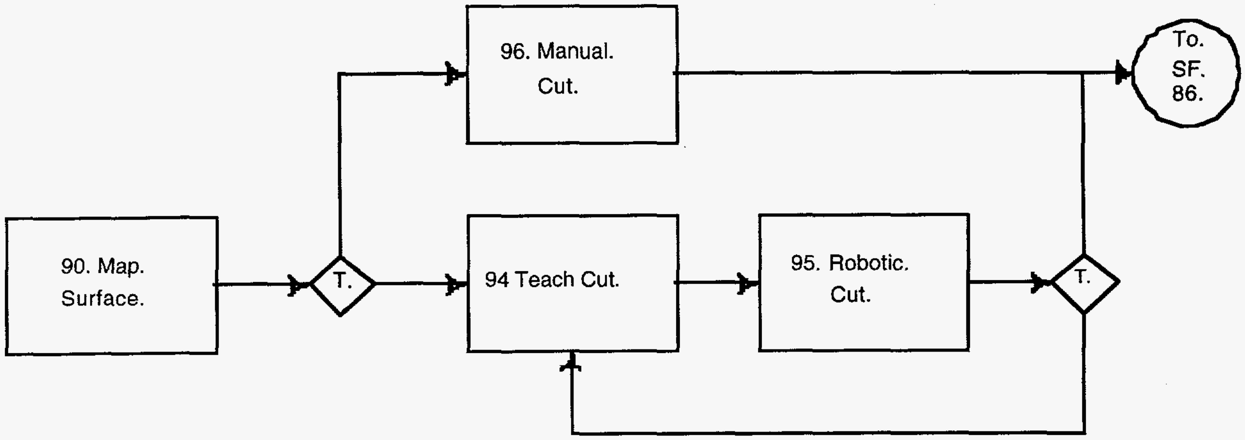

Figure 2. Tasks During the Sub-Function "Cut Risers/ITH."

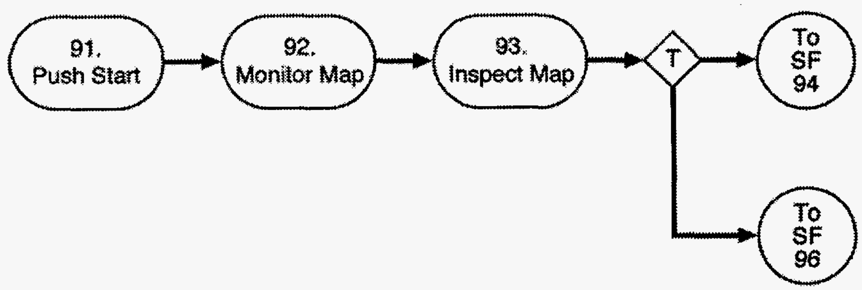

Figure 3. Task Elements During the Task "90. Map Surface."

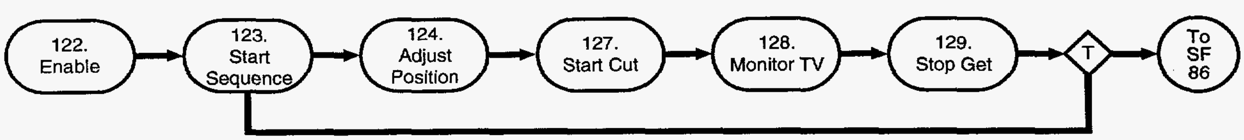

Figure 4. Task Elements During the Task "96. Manual Cut."

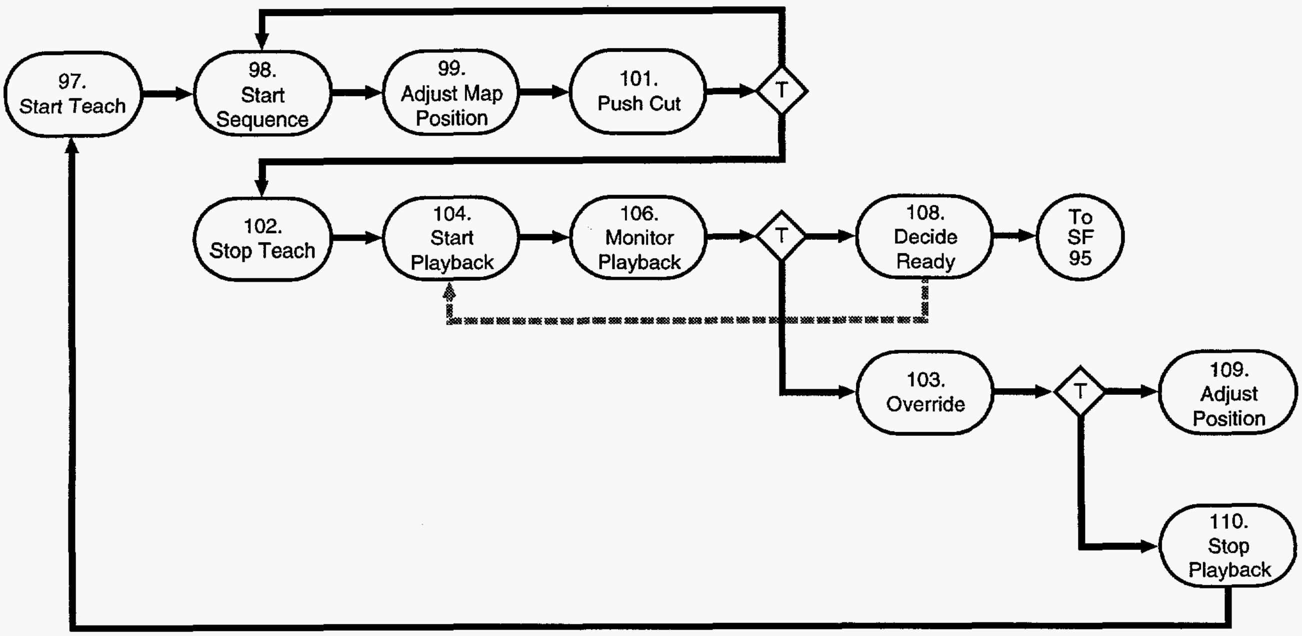

Figure 5. Tasks Elements During the Task "94. Teach Cut."

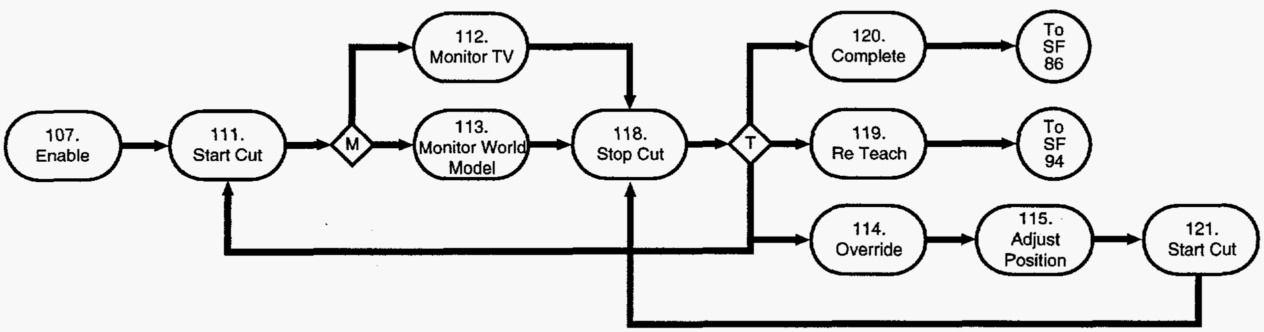

Figure 6. Task Elements During the Task "95. Robotic Cut."

3.2.1 Level of Control

The preceding scenario of control for riser/ITH cutting reflects the supervisory control region of the control continuum with some robotic operations (see Figure 1). This scenario is a combined robotic/semi-autonomous approach in which the cutting tools are moved within the workcell by having the operator interact with the graphical world model (i.e., selecting which riser is to be cut and where it should be cut). Then the sensor based robot control is used to do the actual docking and cutting. This procedure may be considered a case in which the machine controls movement from workspace to workspace within the tank, and the operator is delegated to a higher level task, such as deciding which riser to cut next and where to cut it.

3.3 Task Analysis Example: Remove Waste Layer

During this sub-function, a layer of waste is removed using the appropriate waste dislodging and capture tools. At the end of a repetition, the process is restarted with riser cutting or continues to tank cleaning. The initiating command for this sub-function is *Waste Mapped and Characterized*; the terminating command for it is *Waste Layer Removed.*

The manipulator is responsible for placing the EEs in all areas of the tank, moving the EE at its optimum trajectory, maintaining standoff distances, and controlling velocities and end-of-path accelerations while following tool path planning as directed by the control system. The retrieval operation will consist of a series of horizontal passes over an irregular waste surface, and removing material until that surface has been uniformly reduced in height to the cutting depth required in the mining strategy. Successive steps will produce a conical depression in the waste, sufficient to collect process water and produce a sump for liquid removal as the retrieval process continues. Operational steps include:

1. Verify Mapping by the following steps:
   a.) Verify the actual location of the waste relative to other located equipment, probably by machine vision techniques, or by contacting several mapped features such as the tank wall or waste surface
   b.) Confirm that the elements are in the locations specified.
   c.) Remap as the retrieval process progresses because the distribution of tank contents has changed since they were mapped in previous steps.

2. Plan initial tool path by the following steps:
   a.) Calculate the path for the first planar cut, given the topographical information from the mapping step, and knowing the optimum depth of cut expected by the end effectors.
   b.) The outline for each area should follow successive contour lines, as the height of the waste is reduced to a level plane after multiple passes.

3. Confirm first removal operation by the following steps:
   a.) Remap the surface to assure that the first cut(s) has/have achieved the intended removal pattern.
   b.) Plan the next removal operation.

4. Repeat the mapping/removal steps until confidence in the process has been established.
   a.) Allow mist or fog in the tank to settle between removal operations.
   b.) Excavate carefully the conical depression in the waste without colliding with the waste itself, ITH, or the tank walls.

5. Maintain system as required
   a.) Either change out nozzles as they wear, or
   b.) Replace the entire end effector and remotely maintain the removed unit.

To analyze the level of control required for this task, it is necessary to understand the waste dislodging operations in more detail. As described in Section 2, a requirement for high accuracy in positioning, or a need to control velocity very carefully could present challenges to the operator that cannot be accomplished with manual control. On the other hand, identification of tasks that have less stringent requirements could allow operator choices (either manual or automatic).

For bulk waste dislodging operations, it is assumed that a single device, employing medium- or high-pressure water (15,000 or 55,000 psi, nominal) in a confined scarifier configuration will be used to dislodge the waste that remains in tank C-106 after completion of past-practice sluicing operations. The same system will have additional jets for routine scouring of the tank walls as a part of its dislodging mission.

The dislodging tools defined at present would require movement through a predetermined path with at least five degrees of freedom. Required velocities could be as high as 36in/sec in the horizontal plane, 12in/sec vertically, and at least 0.5rad/sec rotation about the vertical axis; and these velocities must be controlled within 10 percent throughout the waste-scavenging path, maintaining a vertical position within 1 in.

Combined loading on the manipulator from the waste dislodging end effectors is expected to be less than 500 lb., with horizontal loading of 150 lb. applied in any direction during operation. This loading could consist of periodic application of the roughly 80-lb. upward reaction of the high-pressure jets; a similar downward force from the conveyance system suction; or a lateral load from slugging in the conveyance system.

These requirements and resulting forces on the system suggest control envelopes, sensing, and reaction times that will exceed the ability of a human operator to react. This sub-function and the supporting tasks of *Exchange End Effector, Teach Removal*, and *Robotic Removal* are graphically represented in Figures 7 through 10

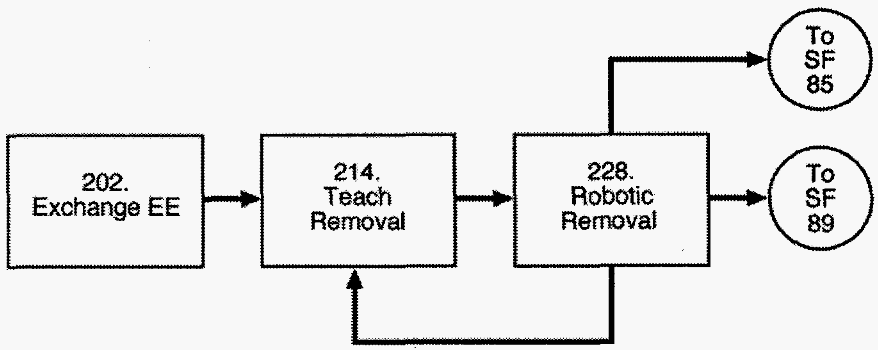

Figure 7. Tasks During the Sub-Function "Remove Waste Layer."

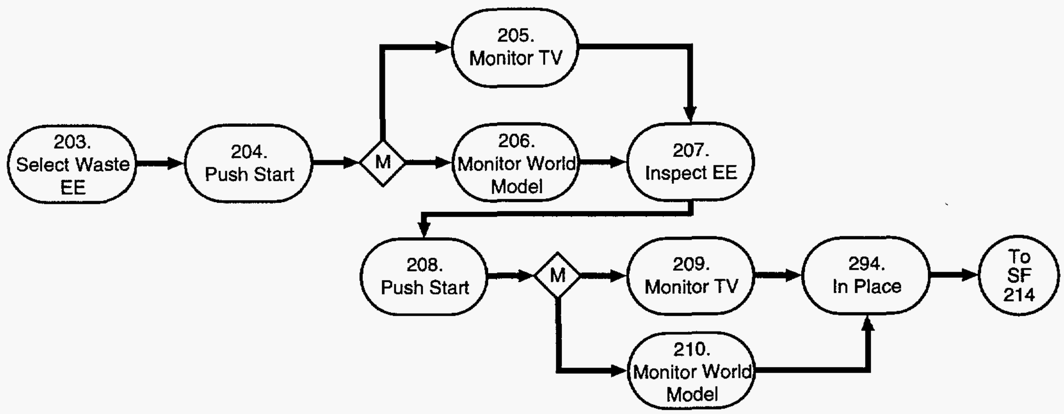

Figure 8. Tasks Elements During the Task "202. Exchange EE."

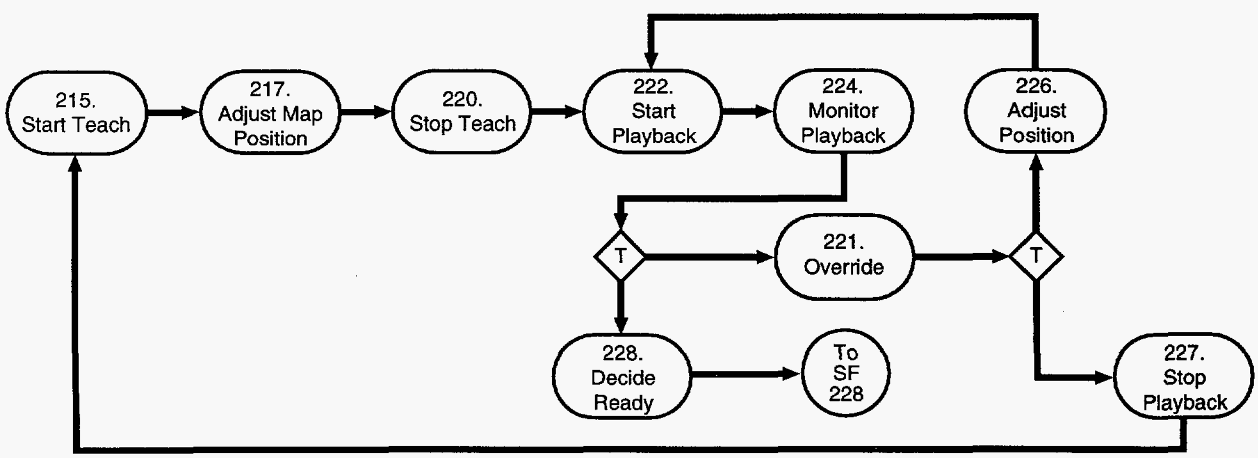

Figure 9. Task Elements During the Task "214. Teach Removal."

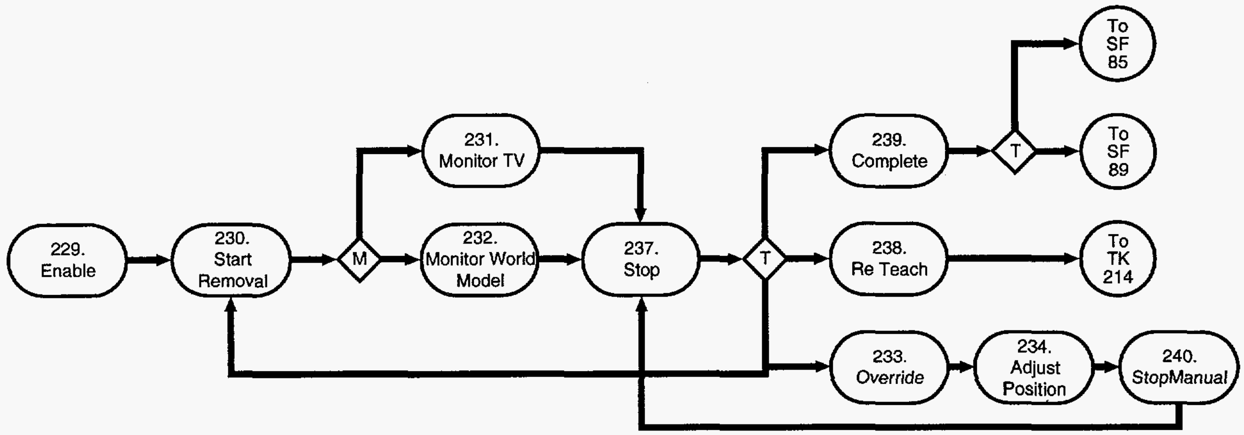

Figure 10. Task Elements During the Task "228. Robotic Removal."

3.3.1 Level of Control

The above scenario is performed with the system operating in the Supervisory Control region (see Figure 1, Level of Control Continuum). It may be completed using teleoperation or robotically, but given the range of movement rates and the positioning tolerances required by the end effectors, it will be difficult for the operator to maintain the appropriate pace and position over an extended time. Therefore, automation is the preferred option for the end-effector performance regimes anticipated. However, because of the unstructured environment of the tank, a human operator must supervise tasks or additional sensors (e.g., obstacle-avoidance sensors) must be used to monitor operations. The human-machine interface must be designed to accommodate human vigilance limitations and task requirements. Furthermore, if this sub-function is performed robotically, the system will require sufficient end-effector-mounted (or lower-arm-mounted) sensors to monitor the position of the end effector relative to the waste surface and sufficient responsiveness and intelligence to respond to the surface in real time. The utility of mapping the waste surface followed by the active use of the EE is also being considered since the sensor performance during EE operation is in question.

3.4 Summary

Detailed analysis of specific manipulator tasks provides some insight into decisions regarding level of control. With a work sequence broken down into individual tasks, the difficulty of each task can be evaluated and the relative merits of manual versus automated control determined. This data can then be integrated and used as a tool to determine the most practical level of control. The next step is to review potential control enhancement features. Section 4 provides an overview of potential enhancements and describes circumstances in which each enhancement would be most beneficial.

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4.0 RANGE OF ENHANCEMENTS

This section describes enhancements that may be applied to the teleoperational control system described in Section 2.3. The enhancements improve the safety and efficiency of operations and reduce demands on the human operators of the manipulator. Enhancements will probably be required for the control system to meet the operational requirements outlined in Sections 2.2 and 3.1.1.

The enhancements described represent a range of technologies and levels of control, from improvements on the traditional teleoperated manipulator to the introduction of telerobotic controls. They also represent a range of maturity, from those that are commercially available to those that are still in conceptual stages. Enhancements may be implemented incrementally; that is, one or more new technologies can generally be implemented to achieve a given performance goal independently of other enhancements. However, certain levels of sensor resolution and system responsiveness are prerequisites for implementation of many robotic controls.

Ideally, the waste retrieval system design will take advantage of the advanced capabilities offered by both robotics and teleoperational enhancements. Although current technology may not be mature enough to allow implementation of full telerobotic controls, it should be noted that robotics technology is advancing rapidly; thus, including certain computer interfaces and sensing requirements in the first generation system will allow upgrade of the system control capabilities as technology becomes available in the years to come.

In some cases, Hanford Site waste tank applications have not been defined sufficiently to allow us to determine the true value of a specific enhancement. In these cases, the benefits of the enhancement are identified along with the circumstances under which the enhancement will be most beneficial. As the Hanford Site task analysis evolves, both on site and as vendors prepare their bids, it will become more apparent which of these enhancements will provide the greatest benefit.

4.1 Enhancements to the Teleoperational Human-Machine Interface

The enhancements described in this section apply to a reference teleoperational system. They do not represent a move toward telerobotics. Implementing these features will improve efficiency and accuracy of operations, with only minor shifts in the level of control.

4.1.1 Telemanipulator Controls

4.1.1 a Input Device-Manipulator Controls

Early telemanipulator designs are powered and controlled completely by their human operators. These traditional teleoperational systems rely on hydraulics, pulleys, gears, and cables as the actuator mechanisms for the input device–manipulator system because of weight-lifting capabilities and back-drivability. A typical teleoperational control system includes little or no capacity for automatic repetition of tasks, so minimal programming capabilities and memory storage exist in the control system. In these basic systems, much emphasis is placed on the monitoring and sensing systems (vision, audio, etc.) and on the display of that information to the operators.

4.1.1 b End-Point Control

Most commercial teleoperational controls consist of an input device (master controller, joy stick, track ball, etc.) used by the operator to control the manipulator arm in the remote workcell. In these systems, the automated control systems perform resolve-rate control (coordinate transformation), allowing the human operators to exercise control over the end point, rather than specifying movements of individual joints. When this type of system is in constant manual control mode, the human operator should control only the end effector, rather than the arm's individual joints. Control of discrete joints, whether by joystick, switches, potentiometers, or other methods may be desirable in some instances but in general, should be avoided because it is inefficient (Goertz 1951; Marjon 1961; Malone 1972; Draper *et al.* 1987). End-point-controlled systems are somewhat more advanced than earlier manual control systems, but the computer capabilities are still modest.

To achieve end-point control, one of two control metaphors may be applied. The user may "wear" the machine as if it were a virtual suit, or "fly" the end effector as if it were a vehicle in three-dimensional space. The performance capabilities of the machine should determine the choice of the control metaphor (suit or flying), but *a priori* user preferences must also be a consideration.

4.1.1 c Industry Direction

Larger, stiffer manipulators and systems require more advanced control to restrain the accelerations and forces generated by the arm. Modern teleoperated systems have adopted approaches that are similar to those used in robotics; controllers of teleoperated devices may have extremely capable controllers and may be easily interfaced with a supervisory control system. As shown in Figure 1 (Section 1), telemanipulators may employ a broad spectrum of control capabilities.

4.1.1 d Synopsis

Computer-based telemanipulation with end-point control is a mature technology that significantly improves controllability of the manipulator. It is routinely employed in commercially available telemanipulators. The retrieval system should provide this capability, which has been included in the reference teleoperational system described in Section2.3.

4.1.2 Force Feedback

Force feedback is an important supplementary sensory channel. To provide force feedback to the human operator, the system must include model based forces or force *sensing* capabilities (see Section 4.3.2 b). Force feedback may be provided in two general ways: force-distribution feedback or proportional force feedback. Extensive research has identified advantages and disadvantages for implementation of and reliance on each method.

Force-distribution feedback provides a display of forces that matches the distribution of forces on the manipulator (usually the manipulator end effector). It gives users a sense of touch, similar to human taction. Craig and Sherrick (1982) review research on dynamic tactile displays for providing force-distribution feedback, but the advantages and disadvantages of these displays for teleoperation have not been adequately explored or documented for applications like those envisioned for TWRMS.

Proportional force feedback presents the operator with a display or reflection of force that is proportional to forces on the manipulator. Force reflection is a type of proportional force feedback in which forces applied by the manipulator (remote) portion of a input device-manipulator system are displayed to the operator through back-driving the master controller. The user feels forces through the action of the input device controller on the telemanipulator input device handle. Proportional force feedback gives users a sense that is not directly analogous to any single human sense, but combines elements of taction (touch) with kinesthesia (the sense related to forces exerted by the limbs and acting on them).

Model based force reflection has also begun to emerge as an important operator feedback mechanism, but has not been fully studied. Since the forces are generated by the controller from mathematical models of the robots workcell and not contact forces, they can be generated in a "near miss" operation and actually warn the operator before actual contact is made. Model based force reflection can be used in combination with sensor based force reflection or alone (without sensors) (Anderson 1993).

4.1.2 a Benefits of Force Reflection

Kugath (1972) found some evidence that force reflection improved telemanipulator performance (defined as task time and collisions with equipment in the remote area) for simple tasks with a fairly large-scale manipulator, but in the author's words, "not enough data was taken to show conclusively that the lack of force feedback was detrimental." However, he observed that removal of force reflection following repeated task completion led to higher rates of operator errors and a change in style: without force reflection, users seemed to execute trajectories step-wise, making a movement and then checking manipulator position before making another input, in contrast to continuous motions observed with force reflection.

Hill (1979) also reported data that seemed to favor force reflection, but his force reflection effects were confounded with differences between the manipulators used in the force-reflecting and non-force-reflecting conditions. Hill and Salisbury (1977) performed an experiment that compared a single manipulator system with and without force reflection. They also found average differences that seemed to indicate force reflection reduced the time required to complete tasks. Draper, Herndon, Weil, & Moore, 1987 failed to find any positive effect of force reflection on the performance of remote handling tasks, but the tasks and procedures used in that experiment may have been insensitive to its effects (Draper, Handel, Sundstrom, Herndon, Fujita, and Maeda, 1987).

Draper *et al* (1987) found that force reflection can be beneficial to operators performing remote handling tasks when the information it provides has no visual analog. Force reflection can be particularly useful when forces in the remote area must be controlled. In their experiment, force reflection did not significantly reduce the time required to complete tasks, but it did lead to significantly lower error rates and forces applied to task components. Molino and Langley (1989) found completion time differences among force reflection conditions early in an experiment, but these disappeared with practice. Hannaford *et al.* (1991) report similar average differences between force-reflection and non-force-reflection modes, but subject performance was so highly variable that the differences were not statistically significant.

4.1.2 b Benefits of Force Visual Display

Several authors have demonstrated visual displays for an indication of force. Hendrich *et al* (1991) reviewed and evaluated this work. These authors also compared participants' ability to moderate forces with these displays and collected participants' evaluations of the displays. While visual displays provide an inexpensive alternative to force reflection, they may place an additional burden on an operator's visual channel, which is already heavily loaded during teleoperation.

Visual representations of force information may also be more difficult to interpret than tactile presentations. However, no direct comparisons of force reflection and visual force displays have been made.

4.1.2 c Benefits of Force Distribution Feedback

Bliss *et al* (1971) studied performance of tasks with force-distribution feedback. This study found no significant differences in the *rate* of task performance with and without force-distribution feedback; however, the *quality* of performance (the number of errors and failed attempts at the task and the strategy used by operators) differed between the force feedback conditions. Without benefit of force feedback, users made frequent imprecise attempts to grasp and operate task components, but users with force feedback made fewer attempts that were more precise and longer in duration.

4.1.2 d Discussion

Certain hypotheses may be stated based on observations from this literature and on the characteristics of humans as processors of information.

There appear to be fundamental differences in the strategies employed by operators with and without force reflection. Kugath (1972) reports stepwise trajectory inputs without force reflection; Bliss *et al* (1971) report different approaches to grasping task components. It seems that operators perform tasks more tentatively without force reflection than they do with force reflection. The ability to detect contact through force reflection may give the operators a greater feeling of safety.

Information provided by force reflection can be unique or it can complement information available through other sensory channels. For example, an operator attempting to tighten a bolt to a criterion torque may be able to judge when the bolt reaches this torque by feeling the reflection of resistance to turning or by viewing the dial of a torque wrench.

Humans tend to favor vision over the other senses. Thus, when force reflection provides information that complements operators' television views of the remote area, operators are less likely to rely on the force reflection (Wickens 1984). Force reflection is most helpful when it displays information that other senses (particularly vision) are unable to provide or when other displays are difficult to interpret.

For the retrieval of waste from the tanks at Hanford, it may not be appropriate to reflect all normal operating forces back to the operator. Normal operating forces generated by the EE and waste conveyance system may overwhelm and even fatigue the operator and desensitize him/her to forces that are important (collisions with the environment). Model based force reflection provides a means to not only scale but filter the approach and contact forces.

The greatest advantages of force reflection present themselves when forces applied to the remote area are important, when task components require guidance or assembly in areas difficult to see with television cameras, and when viewing is degraded by dust, gases, lens browning, or other obstructions.

4.1.2 e Synopsis

Force feedback, particularly force reflection, is a commercially available technology that enhances the operator's ability to perform complex teleoperational tasks, especially those requiring control of forces. Specific applicability to waste retrieval should be determined by further task analysis, specifically identifying what tasks will be performed teleoperationally. The basic controllability needs of the EE seem to indicate that to achieve them teleoperationally, the operator will need every possible benefit, including force reflection; however, if other robotic enhancements are used to control the end effector, perhaps a simpler force feedback would be adequate. The use of model based force reflection seems to be an appropriate means of reflecting important forces back to the operator. Using model based force reflection will allow the operator to feel the manipulator as it approaches a modeled object and can provide a means to filter normal operation forces from those the operator should feel. As an emerging technology that seems applicable to the waste tank clean up efforts, it should be further considered for implementation.

4.1.3 Automation of Auxiliary Equipment

The controls required to operate a teleoperated, remotely located manipulator are far more advanced than those required to operate a manually controlled manipulator. Whereas manually controlled systems generally require only the input device unit and a viewing window, telemanipulator cockpits must include control consoles for auxiliary equipment such as transporters, tools, and television cameras. Teleoperation of a remote manipulator is a high-workload activity, and secondary tasks such as aiming television cameras compete for the operator's attention.

High workload has been addressed by designing telemanipulator control rooms to include multi-operator teams (Clarke and Kreifeldt 1984a and 1984b; Draper *et al* 1988). Hood *et al.* (1990) studied the nature of interactions in a two-person crew.

High operator workload and stress can also be mitigated by implementing automatic controls for some of the sub-tasks. Automatic camera controls have been pursued. Other functions could also be automated, although this may require custom developed systems.

4.1.3 a Automatic Video Controls

Several facilities have researched alternatives to manual control of television cameras. Bejczy *et al* (1980; Bejczy *et al* 1980; and Bejczy *et al* 1981) described and demonstrated how voice input could be used to control telemanipulator cameras, and Frenette (1985) and Draper (1987) verified that voice control and automated tracking (cameras that automatically follow the manipulators) can improve task performance and reduce user workload.

One interesting aspect of automated tracking is that, if it is continuous, the user may lose any sense of manipulator arm movement (Brooks *et al* 1991). This problem can be easily resolved as in a system used by Draper (1987), where camera movement was only initiated if a manipulator arm passed out of a 4-degree deadband area around the camera aiming angle. This solution provides the operator with a "world still -- arm moving" view similar to manually adjusted cameras that does not require operator intervention.

4.1.3 b Synopsis

Within the existing commercial technology, a number of things could be done to reduce the operator workload, particularly in the area of video control. To effectively control the end effector in a teleoperational mode, these improvements would seem to be very useful to reduce the intensity and stress on the operator.

4.1.4 Responsiveness

To move with the same accuracy and speed as a human, a manipulator must be able to accept and execute input commands without modifying the amplitude or frequency of the user's inputs, so that the limiting factor on task performance is the user and not the machine. User inputs are forces/movements applied to a joystick or input device controller handle that produce corresponding manipulator acceleration/position. The optimal machine accepts forces/movements and converts them to acceleration/ position without modifying or constraining the input.

Responsiveness is the ability of a manipulator to reproduce arm trajectories and impedance in time and space. Telemanipulators fall into three categories according to how well they can follow a series of hypothetical human arm trajectories:

1. User-paced telemanipulators are highly responsive and capable of executing any human trajectory in real time.

2. Machine-paced telemanipulators are moderately responsive and are capable of executing most, but not all, trajectories in real time.

3. Non-real-time telemanipulators are incapable of keeping up with typical human trajectories.

These categories represent regions on a continuum of responsiveness rather than fixed categories. No truly user-paced telemanipulator exists, although there are some very good machine-paced telemanipulators.

Although the boundaries of these categories are ill-defined, there is evidence that non-real-time telemanipulators are characterized by maximum end effector velocity below 0.65 m/s (Goertz 1964; Draper and Handel 1989; Draper, Handel, & Hood 1990) and acceleration bandwidth below 1.28 Hz (Draper and Handel 1989), and that user-paced telemanipulators are characterized by acceleration bandwidth above 9 Hz (Draper, 1993a).

4.1.4 a Position Control

User-paced telemanipulators and machine-paced telemanipulators are more efficient when controlled using position control than when using rate (velocity) control (O'Hara 1986; Das *et al* 1992); that is, the user would place the telemanipulator as he/she would position the sleeve of a suit rather than in the way they would control the speed of an airplane. (See Section 4.1.1).

In systems that use position control, the work envelope for a position controller must be large enough to span the task area. If the user frequently meets a work envelope barrier and must index the input device and manipulator (indexing ratchets the manipulator position relative to the input device controller), performance is no better than with a rate controller. Stuart *et al* (1991) were unable to find statistically significant performance differences between position controllers and rate controllers for the same manipulator arm, and their subjects complained of the constant indexing necessary to complete the task with the small-volume input device controller they used. Stoughton (1986) recorded input device controller joint angles during performance of three typical remote maintenance tasks and calculated three-dimensional probability densities for input device handle position. (The users were free to position the telemanipulator transporter in three dimensions to optimize telemanipulator coverage of the work area.) These data show that nearly all operations take place within a volume resting on the user's lap and approximately 3/4 meter wide, 3/4 meter high, and 1 meter deep. Smaller work envelopes imposed by input device controllers require indexing and will reduce efficiency.

4.1.4 b Velocity Control

Velocity is another important performance parameter. When a manipulator velocity limit is greater than users' maximum input velocity the user paces task performance. When a manipulator velocity limit is less than users' maximum input velocity of the machine paces the task.

Users had trouble operating an early (position controlled) servo-manipulator with a maximum velocity of 0.61 m/s (Goertz 1964) but their difficulties disappeared when gear reductions were changed to allow velocities up to 0.91 m/s. During the terminal phase (57% of the time) of a task performed using a state-of-the-art telemanipulator, users moved the input device controller at much lower velocities, but during the ballistic phase (43% of the time), 17% of the velocity observations were at or above 0.76 m/s (Draper and Handel 1989; Draper *et al.* 1990). These figures mean that a machine with a velocity limit below 0.76 m/s will pace the task 17% of the time during ballistic movements.

For non-real-time telemanipulators and low-end machine-paced telemanipulators, velocity or rate control (the flying metaphor) works best because unresponsive systems using position control can develop dangerous lags between input device and manipulator (Draper, Handel, Sundstrom, Herndon, Fujita, & Maeda, 1987).

4.1.4 c Acceleration

Because the user input is force and the machine response is acceleration, observations of hand and input device controller acceleration are useful for identifying important performance parameters. For example, during the first sub-movement in a target acquisition attempt the acceleration impulse bandwidth of the human hand is about 6 Hz. For subsequent sub-movements the average acceleration impulse bandwidth is just above 9 Hz (Van Galen *et al* 1990; Draper 1993a), but Draper and Handel (1993) found that acceleration bandwidth during secondary sub-movements with a state-of-the-art telemanipulator was only 3 Hz.

This low responsiveness was probably caused by input device controller friction and inertia imposed on the user's hand, which made movement more difficult than normal. System loop rates, that is, the lag between command input and manipulator arm movement, and the lag between manipulator-arm action and input device-arm feedback can affect bandwidth as well. For the system Draper and Handel used, the loop closure required only 20 ms, or a rate of about 50 Hz. Observing movements by television may also have reduced the user's ability to judge distances and detect edges in the task, producing uncertainty that may have led to a reduction in the allowable rates of acceleration to permit closer visual monitoring of the movement.

Moreover, in human movements the impact of higher-frequency components naturally has low amplitude because of physiological limitations. A telemanipulator has its own bandwidth that further reduces the amplitude of high-frequency components, sharpening the "knee" of the human-machine frequency/ amplitude function. Therefore, telemanipulator bandwidth should exceed human bandwidth to adequately capture important acceleration components. The best solution for this problem is to develop lighter input device controllers or to determine hand position via sensors not mounted on the user's arm. This solution makes it difficult to provide force reflection, but the sacrifice may be worth the reward.

4.1.4 d Discussion

Human-factors work in teleoperation has concentrated on feedback but the most important challenge for telemanipulator designers now may be to develop adequately responsive manipulators. While Lumelsky (1991) hypothesized that limitations in a user's ability to develop internal representations of remote space limits telemanipulator performance, this seems unlikely given human ability to operate in three-dimensional space. Draper *et al* (1991) provide evidence for this hypothesis. In an experiment that had subjects perform a task

- by hand with direct viewing,
- by hand with television viewing, and
- using a servo-manipulator with television viewing.

They found that the effect of the responsiveness of the servo-manipulator by far outweighed the impact of the use of television viewing. Simply put, internal representations of space didn't seem to be as big a problem as manipulator performance. To date, Fischer *et al* (1990) and Brooks (1990) provide the most systematic approaches to the problem of specifying telemanipulator input devices. To move forward, telemanipulator researchers must concentrate on optimizing the performance of remote equipment. Human-factors researchers can help by defining human performance capabilities.

Shortcomings of position, or rate base input devices, as described in Section 4.1.4 a, Position Control, are also being addressed. Anderson (1993), has successfully shown that superposition of input devices in the control scheme of a rate based controller for coarse positioning of the manipulator and a position based input device for fine positioning tasks can be easily accommodated. The combination of two input devices, both of which can be scaled and indexed separately, can allow an operator to choose the appropriate input device for the task.

Machine performance parameters may vary within a single machine. Draper *et al* (1986) found that users moved a telemanipulator using two joint clusters corresponding to a slewing cluster involving joints that moved long (arm) links and a fine-adjusting cluster involving short (wrist) links. Draper *et al* (1991) found further evidence of these clusters when examining the impact of failures on another telemanipulator. These results, along with the joint velocity observations mentioned above, imply that arm joints may be relatively low-frequency joints with high-velocity limits and wrist joints may be high-frequency joints with low-velocity limits.

4.1.4 e Synopsis

Research indicates that manipulator responsiveness is directly related to task performance. Considering the difficult control problem envisioned for the waste retrieval task, additional responsiveness seems beneficial. However, for the large manipulator planned for the waste retrieval effort, this conclusion implies significant translational speeds and inertial energy, which raise concerns relative to protecting other in-tank equipment.

If the end effector is to be controlled teleoperationally, careful design consideration will need to be given to provide adequate responsiveness while simultaneously protecting other in-tank equipment. Because the operator can adapt best to the most responsive joints, a design using a "light" manipulator on the end of a "heavy" manipulator may help alleviate this problem and the use of more than one input device in the control system may also improve the operators control over the retrieval system.

4.1.5 Computer Enhanced Human Machine Interface

Human factors usually affect both the way the human-machine interface structures the user's task and the design of the human-machine interface itself. In teleoperation, human factors can be even more critical because the design of the controlled system should make use of human performance data. This conclusion does not apply to the design of an advanced tactical aircraft, for example, because

- there is no analogous human performance (how fast people can fly without machines),
- powerful natural preconceptions do not mask the mental models users develop for systems (expectations about how arms behave are reinforced daily), and
- the actions of most systems respond to the user's inputs but do not mimic the users' inputs (as is the case with highest-performance telemanipulators).

As Hogan (1989) said, "In teleoperation, the [human-machine] interaction... is more than merely an exchange of information — energetic interactions are at least as important."

The design of human-machine interfaces for telemanipulators is a demanding task because of the requirement for real-time reproduction of hand and arm movements. However, since computers link the user to the servo-manipulator, system designers also have the tools to adjust the user inputs and displays to improve operability.

For example, animations may be overlaid on television pictures to show parts of the environment obscured from the view of the television camera. Brooks *et al* (1991) list some display aids for teleoperation.

It is also possible to change the scale of the work. A user could repair a heart valve, replace piping in a process plant, or capture a satellite from the same control station -- all within the same work envelope if the input device controllers can communicate effectively with manipulator arms of appropriate size for the real-world tasks (Flatau 1973; and Rasor and Spickler 1973).

4.1.5 a Synopsis

Enhancing the feedback to the operator will improve the performance of the teleoperated system. High-fidelity information displays and control outputs relate directly to increases in operator performance and should be incorporated whenever practical. New and emerging technologies that increase telepresence are a thriving area in many industries (not just robotics). It is very likely that advances on these fronts will continue to have a favorable impact on increasing the operator's telepresence and thus performance. With the difficult control problem envisioned, advantage should be taken of these capabilities.

4.2 Robotics Enhancements

The availability of increased computer power and more powerful processors in smaller packages has enabled significant advances in the field of robotics or automatic controls. Advances in powerful distributed multitasking capabilities have greatly extended the capabilities of robotics in many fields, but are specifically enabling intelligent machines to present viable solutions and allowing robots to work in unstructured work environments, such as may be encountered in Hanford Site waste retrieval application.

The enhancements described below represent increased levels of automation that rely on these advanced processing capabilities to alleviate demands on human operators and increase the accuracy and efficiency of waste retrieval tasks. In terms of levels of control, implementation of these enhancements represents a shift from the reference system toward the robotic end of the continuum (see Figure 1).

Since its inception, the DOE's Robotics Technology Development Program has continued to develop robotic technologies that can be used in the environmental management at sites within the DOE complex. The feasibility and applicability of the technologies developed in the RTDP have been demonstrated, and several have been transferred to industry through Cooperative Research and Development Agreements (CRADAs) and licensing agreements between the national labs and the commercial sector.

4.2.1 Supervisory Control

A basic premise of the supervisory control approach is that sophisticated robot system performance can be obtained by coordinating the operation of a collection of subsystems each with complimentary capabilities. This approach is analogous to a team of highly skilled individuals where each team member has particular skills which, under the supervision of a team leader, integrate with the skills of the other team members to provide a highly effective group with problem solving abilities beyond those of the individual members of the team. As problems change, the team may be modified by the addition or substitution of members to add specific skills, but the basic structure remains intact as well as many of the original team members.

Consequently, supervisory control is not a single entity but an approach to synthesizing highly capable robot system controllers through the assemblage and coordination of specialized subsystems. Each specialized subsystem must be capable of responding to directions from the supervisory level (i.e., the team leader) and reporting information to the supervisor needed for proper decision making. This requirement for interaction with the supervisory level and carrying out actions based upon those commands defines the compatibility of the subsystem with the supervisory control approach.

4.2.1 a Using A Supervisory Control System

During supervisory control of a teleoperated manipulator a user carries out a mix of five tasks (Draper, 1994).

1. Controlling, continuous manual control
2. Teaching, storing specific workcell locations through examples or operator specified points
3. Programming, storing a behavioral repertoire or sequence of actions

4. Commanding, control via manipulating symbols to execute the program or previously stored commands
5. Monitoring, observing the machine carry out commands and deciding to switch to one of the other tasks as required.

Full manual control still exists as a sub-task of supervisory control. By implementing supervisory controls, the system designers do not relinquish manual control over the manipulator. Supervisory control adds the functionality that, generally speaking, gives the system some autonomy that the operator supervises. The programming and teaching of a robot can greatly reduce the level of demands on the operator.

Teaching the robot a complex task through the teaching of points, paths, and sequencing in the workspace is a typical supervisory control function. Once taught the procedure, the robot can repeat the task autonomously, and when sensors are included in the control scheme, even perturbations in the task can be accommodated in this automatic mode. Common examples include the location of tools that the robot will need to access during the execution of a task, or a stowed position for insertion and extraction from the tank. The automatic changing of tools can illustrate the example of how the ability of the robot to store points and paths can ensure safer operation. When the robot is required to change tools, the current tool is stored at a specific location in a tool holder. The entire motion of moving from any point in the work space to the location of the stored tool can be automated by teaching the robot where these points are in the workspace. Small portions of the task, such as the opening and closing of the robot gripper to hold the tool, are automatically executed under the watchful eye of the operator. The program can then continue by instructing the robot to retract to a safe distance from the tool rack. If the point where the operator stopped the work to change tools is saved, the robot can return to the exact spot of the workcell and continue with a new tool.

Commanding and Monitoring Operations are significantly simpler by the assistance of the computer controls. Supervisory control enables entire complex sequences of operations to be performed with minimal operator intervention. Using the above sequence of tool change out, it is clear that:

- The programming of the robot reduces the level of demands on the operator,
- Safety is increased since the robot goes to known obstacle-free points, and
- The operation is faster since change out is done under computer control.

Supervisory control can also lessen the level of demands on the operator, increase safety, and, in many cases, result in faster operations, as presented in Section 3.0.

4.2.1 b User Interface for Supervisory Control

A supervisory control system can employ the same user interface and the same input device as a teleoperated system, but would logically include more, or different, equipment for an optimum operator interface that would include both a teleoperated and supervisory controlled robot system. Common supervisory controlled systems use a graphical display to provide the operator with additional feedback mechanisms derived from the programming of the robot; a view model based on collision detection; and the capability for the operator to change his perspective/view of the workcell without being tethered to the hardware cameras. Input devices to record points or paths can use a keyboard, or graphical user interfaces such as a mouse or a space ball.

The supervisory control system would logically include more than that provided with a robot, since several robots and sensor systems need to be controlled in a coordinated fashion. A typical industrial robot includes a terminal where operators type commands on a keyboard and receive feedback that the command was acknowledged or rejected through text displayed on a video monitor. A teach pendant, generally a hand-held device, is generally included with the robot, which can be used to perform all, or many, of the operations done with a keyboard. The teach pendant's portability allows the operator to move around in the robot's workcell and program the robot with the hand-held device by typing words or using symbols on the teach pendant. Feedback on the teach pendant is usually a small liquid crystal display (LCD) display. A graphical system provides much more feedback to the operator and eliminates much of the trial and error required to program a robot through text based or teach pendant programming, and increases the speed of programming the robot.

4.2.1 c Synopsis

Although supervisory control is not specified in the reference system, it is probable that a system lacking supervisory control will be unable to meet the requirements outlined in Section 2. In any case, it is certain that implementing supervisory control will take some of the burden from the operator and allow safer and faster operation while overcoming the shortcomings identified and allowing the anticipated subsystems (sensors, robots, end effector control, conveyance control, etc.) to be used and controlled in a coordinated fashion.

It should also be noted that supervisory control is somewhat of an umbrella encompassing many of the other enhancements. It is an enabling technology, which can take on various sub-sets of the other described enhancements to increase the level of automation.

4.2.2 Graphical Programming of Robots and Simulated Motion

The need for graphical programming may best be illustrated by explaining the programming of a robot without the advantage of a graphical programming environment. In programming an industrial robot to move from one point to another point, the operator is responsible for ensuring that the path is appropriate (that no collisions will occur, for example.) A robot has very little information about its workcell; it knows about itself through its kinematics, and the points and paths that it is taught by the operator. Obstructions in the workcell, however, are difficult to teach a robot. If, for example, the robot is near the steel liner of a tank and is instructed to move to the other side of the tank, it can get there in many different ways. It could rotate about its waist causing the end to follow the circumference of the tank with possible interference with in-tank structures, or it could rotate up, about its shoulder and go toward the tank dome. Because of a robot's joint limits, some possible moves are not obvious before they are completed. In a robot programming environment without graphical previewing, it is the operator's responsibility to ensure that in a point-to-point move the path is appropriate and collision free. The paradox lies in the fact that the operator can only see the adequacy of the path when it is executed by the robot.

The important concept in graphical programming is that the graphical representation is not just a picture to be manipulated, it is the supervisory computer's means of storing knowledge about the robot and the workcell. The graphical model that is presented to the operator is based on mathematical representations stored in the supervisory computer. The information about the robot's work cell is called the world model. Because the objects are mathematical entities that the computer can "understand," they can be used to control and plan robot motions including obstacle avoidance. Motions can be previewed before they are executed by the hardware to ensure that an appropriate motion has been commanded.

Graphical programming of robots allows the operator to manipulate a graphical representation of the robot hardware and visualize both planned and actual movements in an intuitive manner. When the operator observes a planned movement of the robot, he/she knows where and how it will move to a specific point. This information inherently increases safety and the operator's confidence in the system. Graphical programming extends the knowledge about the work environment for use in the control of the robot system because it allows a robot to perform most conceivable tasks more quickly than if controlled by line-by-line coding or trial-and-error (as with a teach pendant).

4.2.2 a Improved Visualization

Graphics-based robot simulation systems are used in the operator interface for programming, controlling, and monitoring the robot systems. Operators can manipulate the graphical image in a variety of ways: using standard screen input devices such as a mouse; common 3-D input devices such as a space ball, dial box, or robot input device; or higher level inputs such as voice commands. Some of the pioneering work in the graphical programming arenas for the on-line programming of robots is found in Christensen and Desjarlais (1990); Christensen *et al* (1992); Harrigan (1988, 1989, 1990). McDonald and Palmquist (1993) have described the graphical programming approach and the standard computing structure on which it is based.

A Graphical User Interface allows the operator to interact with the model because the intended robot motions can be seen from any angle, position, or magnification, and the operator can modify the motions of the simulated robot before they are executed by the real robot. Paths and collisions can easily be viewed or detected during the graphical programming process.

4.2.2 b Graphical Path Planning

The supervisory controller must also know about the robot(s), but this knowledge is even more important for graphical programming. The kinematics of the device must be accessible to the graphical system so that the simulation knows what action the robot will take when the command, or program, is sent to the hardware. This intimate knowledge about the robot behavior by the graphical control system allows moves to be previewed (or simulated) before they are executed by the hardware.

Graphical programming can be as simple as instructing a robot to move between stored points (commonly called tag points); or complex sequences of activities can be performed. These include changing the tooling or execution of a complex task, such as painting a structure or planning a waste dislodging campaign for a tank around risers, obstacles, and tank boundaries. SNL has defined complex paths in a graphical programming environment that requires tens of thousands of points. It has developed the program (and not only the path) of the robot to follow, but also the control of the EE (such as when to turn it on or off over the path). All programs can be viewed in simulation before they are down-loaded and executed by the robot system, and they are an integral part of graphical supervisory control.

Advanced path planning may also be necessary in the retrieval of waste from the Hanford tanks. For example, as the robot enters a full tank that has several risers it may be extremely difficult for the operator to position the robot arm(s) with the constraints imposed by the waste, risers, and the kinematic limits of the arm.

Automated path planning can find a solution, if one exists, for positioning the arm in the congested environment. (Chen and Hwang, 1992). This capability not only provides a level of safety not possible with a telemanipulator or point-by-point programming of a robot, it also speeds up the programming and task execution.

4.2.2 c Real-Time Tracking

The benefits of graphical control go beyond just program setup. Graphical control also allows for real-time tracking of the system; i.e. as the robot system executes the task, the supervisory controller reads the robot position, and the graphical image is updated accordingly. This direct correspondence between the robot and the graphical image allows the system operator to quickly and effectively act on this information.

The Supervisory Control system can command sensing systems to locate new or moved objects (e.g. fixtures and workpieces) in the environment and display those sensed object in the graphical environment. The real-time tracking also provides a continual quality audit function from insertion to extraction.

4.2.2 d Discussion

McDonald and Palmquist (1993) have summarized the advantages of graphical programming. Graphical programming systems improve system safety over competing systems in several important ways:

- Hazards are predicted through simulation and locked out through program control.
- The operator is warned of motions that would cause near-collisions (with a larger near-miss distance set by the operator for earlier warning).
- Motions that could cause collisions cannot be given to the robot unless the operator has specific override permission.
- The quality audit function of linking programming to monitoring is a thorough method for verifying that safety calculations are correct.
- The supervisor remains synchronized with the real world and, therefore, safety checks remain accurate even when the robot's operating environment changes.
- Software reuse allows supervisory software to be quality verified in many situations.
- Advanced technologies can be integrated to improve operator efficiency without reducing safety.

4.2.2 e Synopsis

Graphical programming can make significant contributions to the safety and speed of robotic operations and it is recommended where technology is available. It provides an input channel that the operator cannot have with hardware by allowing the operator to view the entire workcell from any vantage point and at any distance without having hardware cameras present. The augmentation of the video cameras with the graphical world model provides the operator with additional flexibility in operating the robot. Graphical programming allows only safe (i.e. collision free) moves to be executed and it informs the operator what path the robot will take through a graphical simulation before the program is executed by the hardware. The speed of completing some tasks can be faster with graphical programming, but it is also meant to be used in conjunction with teleoperated control. Each is used where speed and safety issues are optimized for a specific task.

Because both speed and safety can be increased through the use of graphical programming, it is recommended as a technology that should be included on the Hanford tank retrieval system.

4.2.3 Sensor-Based Robot Control

In many robotic applications, especially in unstructured environments, it is desirable to have sensors aid the robot in executing its activities. Either the robot controller, or the supervisory controller, use input from additional sensors to accomplish a task. For example, a force sensor is often used in robotic applications to measure or limit the amount of force a robot can apply to its environment. Many industrial robots can be easily fitted with a sensor, usually in the wrist, that will measure forces and torques. Properly equipped, the robot can be commanded to touch any surface with a desired force. Section 4.3.2 further discusses various enhanced sensing capabilities. This section focuses on their use in controlling the robot.

The addition of advanced sensing capabilities improves the robustness of the graphical modeling by providing data to complement the measurements, or approximations, used to generate the graphical model. Additional sensory feedback is especially important when contact or close proximity with the real world is required. For example, if a robot is instructed to touch an object using only the measurements included in the graphical world model, a measurement error of 0.001-inch will prevent the robot from touching the object or worse yet, cause a collision that could generate high impact forces. These problems are alleviated by using auxiliary data from sensors and controlling the robot by the sensor readings.

Using sensors in the control loop can also be advantageous when a robot is used in a teleoperation mode. By the same analogy, the robot could be teleoperated to touch a surface, but the force is not allowed to exceed a user-defined threshold. Thus, no matter how hard an operator pushes on the input device, the controller will not allow the threshold to be exceeded.

4.2.3 a Technology Demonstration

The benefits of sensor-based control used in conjunction with graphical supervisory control were demonstrated by the RTDP team in the Hanford Underground Storage Tank Demonstration in November 1992. Combined sensor integration and sensor control were critical to performing semi-autonomous, in-contact operations. The task of cutting a piece of pipe using a robotic system was chosen to demonstrate the ability to remove in-tank hardware without disturbing the structure attached to the hardware and without causing inadvertent contact or forces with the robotic system. Operator assistance in the positioning of the cutter was appropriate because the cutting system needed to be in contact with the pipe, and it used a large Spar robot as well as a Schilling robot that could easily generate thousands of pounds of force and damage the structure.

The overall system consisting of the Spar, the Schilling, and the tooling is over thirty feet in length. The robots were connected in a serial chain and had ten degrees of freedom. This system can be extremely difficult to teleoperate when it lacks an intuitive operator interface. By using graphical and sensor-based control, the task of placing a hydraulic pipe cutter around a pipe was easily accomplished by

- Generating a surface model (topological data) of the tank with a structured light system
- Importing the surface model into the simulation system model. (Structured Light Data in Figure 11.)
- Generating initial tag points on the sensor generated world model
- Modeling and testing a path to the tag points
- Commanding the cutter to dock along a simulated path
- Correcting the actual path through sensor feedback from acoustic sensors on the cutter
- Measuring the actual pipe diameter using other sensors on the cutter.
- Performing final positioning of the pipe in the cutter based on the measured pipe size.
- Commanding the hydraulic cutter to stroke.

Although a fairly long list of actions is required, it should be pointed out that the graphical control and sensors make the operation semi-automatic, the operator needs only instruct where to cut and monitor robot progress. Once the structured light data was imported into the world model, the operator only needed to select the docking operation, click (using a mouse on the graphic screen) on a point in the world model for an initial goal point, approve a simulated robot motion, and command the cutter to cut after the robot successfully docked the cutter. The docking operation took less than one minute.

4.2.3 b Discussion

This cutting sequence should be compared to Figures 4, 5, and 6 in Section 3. Although there are more steps involved in a robotic cut, coarse positioning and fine alignment in a manual cut can be very time consuming and cause excessive operator fatigue. Even with an adept operator, small errors in positioning must be tolerated. But it must be stressed that the forces that the manipulator system can generate due to small positioning errors can be very large and can be unacceptable.

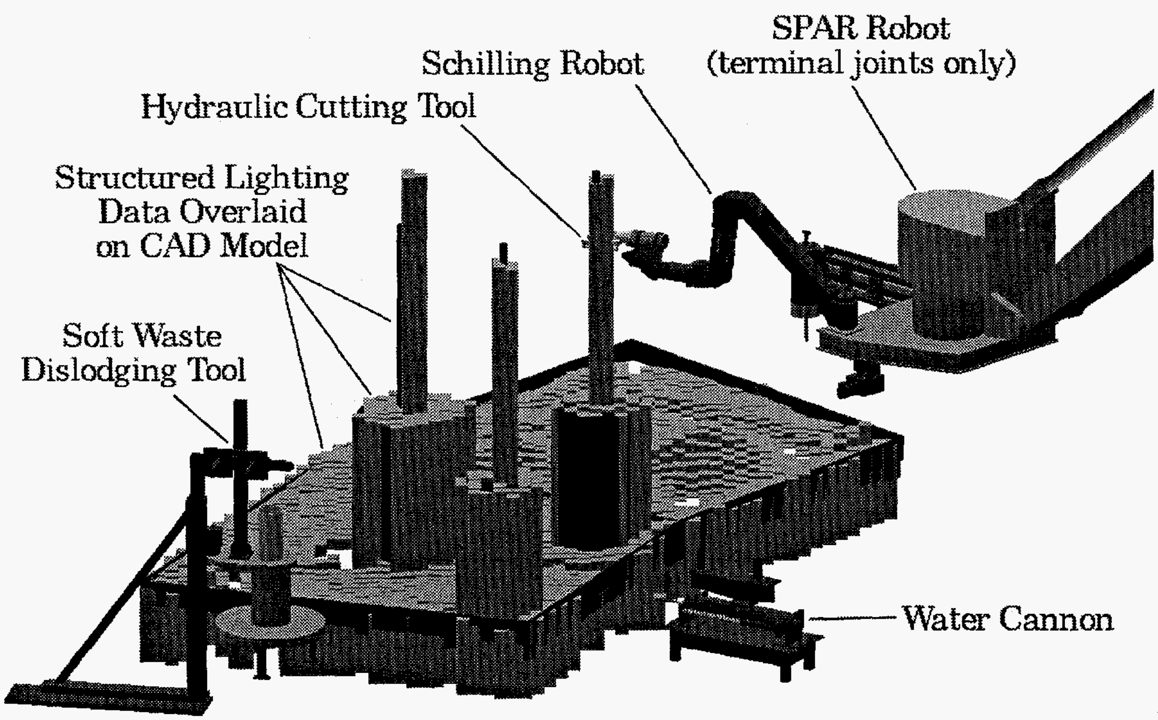

Figure 11. Graphical Representation of a Robot Workcell

Sensor based control is perceived to be needed in other aspects of the retrieval process also. Sensor-based control can be used to aid the operator in positioning of the waste-dislodging tools. As mentioned before, many of the candidate waste-dislodging end effectors are based on water jet technologies that are currently believed to require a tight standoff tolerance, of 1/2 to 1 inch, from the waste surface to efficiently operate. Using that equipment, it is probably unrealistic to expect an operator to maintain these standoff distances and maintain the proper path and speed during the months that would be required to remove the waste from a full tank. A proximity sensor that measures the distance from the waste dislodging tool to the surface of the waste could be used in the control loop to maintain the tool distance from the waste. This would allow the operator to specify a path, and the sensor would ensure that the end effector, within the tolerances of the sensor and the robot system, stays the proper distance away from the waste surface. This level of control would help protect the equipment, increase system productivity, and help ensure that proper procedures are followed.

4.2.3 c Synopsis

Sensor-based robot control is a mature technology that has been demonstrated to be feasible and effective in assisting in the tasks required to retrieve tank wastes. Sensor based control is not common in industrial settings, since the environment in which the robot operates is structured and position based control is sufficient. For the unstructured environment in the Hanford tanks, it is highly desirable (and probably necessary) to use sensor based control to accomplish the retrieval objectives. As a minimum, the control architecture for the retrieval system should be able to allow the sensor based control technology to be incorporated.

4.2.4 Industrial Robotic Control Capabilities

4.2.4 a Controller Hardware

Industrial robot controls are typically designed to be specific to the robotic system for which they are designed. Until recently, commercial controllers relied on an analog-servo system for control of the primary actuators (electrical) for the individual joints of the robotic arm. The control architecture generally consisted of loading a desired set of trajectory points into the analog servos and using digital controller commands to start the motion and check for stopping conditions.

The serial interface used to communicate to the outside world was typically an RS-232 electrical interface. This has been adequate for communications to equipment such as a pan and tilt units or other equipment that can tolerate low-to-medium data rates.

In recent years several robotics vendors have worked on improving the controller hardware for speed and additional control features because of advancements in computational capabilities. This effort is limited to a few vendors because industrial sites do not usually need real-time control capabilities.

4.2.4 b Controller Functions

Robotic controllers are equipped to serve as a limited operator interface for maintenance, setup, programming, and debugging. The controllers have memory facilities for long-term, non-volatile program storage, and can interface with other industrial equipment either through the general networking line or through dedicated control lines.

Control instructions typically include commands such as "start/stop," "go to home or calibration position," "enter teach mode," "leave program mode," "store or retrieve program." The controllers can also monitor internal and external conditions related to the proper and safe operation of the robot (load ranges, movement limits, temperature, etc.).

Most commercial robot controllers are equipped with text based control programming language and a teach pendant as the primary human controller interface.

4.2.4 c Discussion

Industrial robots are oriented toward tasks which are high in volume and very structured. The robotic systems are programmed by operators for large batch operations by a teach pendant input device or off-line programming. Operations typically programmed consist of predictable tasks that are repetitively performed in a controlled and known environment with speed and accuracy.

4.2.4 d Synopsis

Industrial robots are oriented toward repetitive, structured operations, which is different from the expected in-tank environment. Adding a supervisory control system "above" the robot allows rapid "re-programming" to accommodate the changing tank environment.

4.2.5 Merging of Teleoperation and Robotic Controls

The recent evolution of teleoperated manipulators has been toward more autonomous operation to reduce operator fatigue and improve operator productivity and to accomplish tasks that could not be performed manually. The evolution of robotics technology has been toward less structured applications through sensor-based controls and improved operator controls.

With both ends of the spectrum merging, a more modern generation of telerobotic systems will be readily available with multimode controllers. Multimode refers to the incorporation of sensor-based control, graphical and model-based simulation and control, improved teaching methods, high-level language support in the autonomous mode, and an interactive user interface, collision avoidance, and enhanced teach playback in the interactive (or teleoperational) mode, with the ability to move seamlessly between the two modes.

Commercial vendors realize this opportunity, and many are actively working to enhance their current teleoperational and robotic controls to merge toward telerobotic controls. They are actively pursuing flexible and versatile open architecture control platforms, with multi-mode control, and real-time monitoring of the internal and external environment.

Several comparison studies have been completed in the last year on advancements in controller capabilities (Ford, 1994; Holliday 1993) that merit review and consideration when determining requirements for the waste retrieval system (Merrill, 1993).

4.2.5 a Synopsis

This problem points out the need to keep our options open, to be able to incorporate the new technology as it becomes available. By its modular and expandable nature, a robotic system with supervisory control provides the best posture for enhancement.

4.3 Sensor Enhancements

As discussed above, advanced sensing capabilities enable a number of advanced control systems. Primary emphasis is on accurate visual representation of the tank, but because the tank environment may be difficult to see, a number of other sensors are explored. Most of the industrial performance enhancements discussed below have been through previous lengthy development processes. Many of the same capabilities have already been integrated and tested to some degree in nuclear environments. Those that have not been previously integrated into a nuclear environment will require radiation and environmental hardening, and only minimal adaptive development is envisioned after the sensor is hardened.

4.3.1 Vision Capabilities

The most important telemanipulator feedback mechanism is a television view of the remote area. Mono-image television (MTV) is sufficient for teleoperation, but it provides less information than normal because

- it presents a monocular view to both eyes, while normal human vision includes binocular (or, two slightly different) views because of the separation between the eyes; and
- the individual sees less in the format because video resolution is less acute than human perception.

The normal image difference between the eyes is important because it produces a cue to distances called retinal disparity.

Some researchers suggest stereoscopic television (STV) as a desirable alternative to MTV because it displays two different views of the remote area, one to each eye, and therefore provides retinal disparity cues (and convergence cues as well). Spottiswoode *et al* (1952) and Dumbreck *et al* (1987) described the geometric principles involved in presenting an accurate stereoscopic representation of space and the distortions produced by failing to properly control viewing system geometry. However, they did not attempt to describe how the human visual system prioritizes and integrates the available cues in a televised scene. Their models do not provide guidance about the utility of STV, but concentrate on describing how to provide good stereoscopic images.

4.3.1 a Mono-Image Television (MTV)

Although retinal disparity is not available with MTV, other sources of depth information are. Therefore, it is incorrect to associate depth perception solely with STV, because depth perception is possible with MTV using cues like perspective, interposition, shadows, and object size. The richness of all the cues available in a scene, not just the binocular ones, determines the accuracy of distance estimates and the subjective experience of depth. Smith *et al* (1979) provide the best summary of performance differences between STV and MTV. They say, "It is obvious that in a full-cue viewing situation, where there is a rich and redundant set of cues indicating object distances and identities, it would be possible to take away several redundant cues without taking away depth perception."

There is also evidence that monocular depth cues are more powerful than binocular depth cues under some circumstances, specifically when judging distances between objects on a single plane, and as powerful as binocular cues under most circumstances (Stevens and Brookes 1988).

Furthermore, there is evidence that increasing viewing system resolution is at least as important as providing stereoscopic images for remote handling tasks and visual inspections (Draper, Fujita, & Herndon, 1987), and resolution has been shown to be an important determinant of text legibility (Gould *et al,* 1987). Unfortunately, the impact of resolution on teleoperation has not been as thoroughly studied as the impact of stereoscopic images, perhaps because increasing resolution requires a more extensive modification of existing televisions.

4.3.1 b Stereoscopic Television (STV)

The debate on the utility of stereoscopic television for teleoperation has two fundamental positions. One position is that stereoscopic television affords users more information about the remote area and, therefore, must improve telemanipulator performance. From this position, experiments that have failed to demonstrate the STV advantage have lacked power or used poorly designed viewing equipment. The second position is that STV affords users more data about the remote area, and if these data are unavailable through mono-image television, or more efficiently converted to information in the presence of STV, it will improve telemanipulator performance.

To date, a critical experiment comparing these two positions has not been performed, and in fact it is difficult to imagine data that could refute the first position. A third position holds that STV has a negative impact on teleoperation because it induces fatigue and eyestrain, but this may be discounted as a response to sub-optimal STV design. Systems with low data rates that cause visible flicker, large inter-camera distances, poor image registration, or heavy head gear can induce fatigue or eyestrainor neck strain but these factors should not be construed as indictments of STV.

Certain hypotheses concerning the impact of STV on telemanipulator performance may be derived from examining the literature.

- First, the viewing conditions in the remote area have an impact. Users seem to perform better with STV than with MTV if the task area is obscured (Pepper and Cole, 1978). However, under these conditions the important impact of STV may be to improve visibility rather than depth perception per se because of the positive impact of binocular concordance (Jones and Lee, 1981).

- Second, environment and task characteristics have the impact that predictable, structured tasks and environments seem to afford enough information to make STV redundant, but unstructured or dynamic environments do not (Pepper and Cole, 1978; Draper *et al,* 1991; Drascic, 1991).

- Third, user characteristics have an impact because performance seems relatively unaffected by the presence of STV after practice (Smith *et al,* 1979), perhaps because users become better at seeking out mono-image cues.

- Fourth, characteristics of the controlled system may be that less responsive manipulators require more precise positioning because users are not able to recover as quickly from perceptual errors.

- Finally, users are active information seekers (Gibson, 1966) embedded in a multi-sensory system. Users may attempt to compensate for the loss of stereoscopic information by manipulating the remote environment to test and modify their world model. When the telemanipulator is responsive enough to allow this, binocular vision may not confer strong performance advantages (Jones and Lee, 1981).

To summarize, the performance advantage for STV may be inversely related to image clarity, task complexity, user skill or experience, and manipulator dexterity. However, some of these factors are not well quantified. The precise nature of the relationship between them and performance is not clear, and the interactions among these factors are unknown. The definition of performance is also important. STV may not improve task completion time, but it may make movements more accurate and hence safer.

4.3.1 c Camera Placement

The placement of television cameras in the remote site can also be a difficult problem. Often, viewing systems have the lowest priority in design of a remote maintenance system, and as a consequence camera placement is on a space-available basis. This can lead to cameras with lines of sight that are easily occluded by the manipulator or dramatically different from normal lines of sight from eyes to hands. Smith and Smith (1987, 1989) summarize some experiences with the impact of lines of sight on television viewing during sensory perturbation experiments.

4.3.1 d End-Point Tracking

End point tracking, also referred to as robotic visual tracking, "refers to the capability to move the manipulator so that the projection of a moving or a static object is always at the desired location of the video image" (Papanikolopoulos et al. 1993). The camera systems can be mounted on the manipulator itself, or they can be statically located, provided that the camera views are not obstructed. Considerable work has been done to develop adaptive control algorithms for real-time end-point tracking. Such algorithms are typically based on the on-line estimation of the distance from the target to the camera system. These distances are used in the adaptive control algorithm that creates commands sent to the robotics controller system for driving the manipulator. Recent advancements in computers have made enough computational power available for real-time robotic visual tracking.

This capability has been shown in several RTDP demonstrations (e.g. waste processing operations) with commercial hardware (Harwell stereoscopic vision system) coupled with an adaptive controls algorithm. Other experiments have been completed using laser range finders as the sensory feedback device (Venkatesan and Archibald, 1990). The advantages of end point tracking are to be able to track action occurring at the end of the telerobotic arm or the end effector. This function enables the operator to monitor progress and to make decisions based on the visual feedback more effectively. Automated tracking capabilities free the operator from having to determine the camera positioning simultaneous to the telerobotic positioning, leaving the telerobotic manipulation as the operator's primary activity. Coupling the hand-to-eye coordination is often referred to as "look and move" or "eye in hand" vision.

The supervisory controller has also been used within the RTDP to perform end-point tracking. Since the supervisory controller should not be limited in the type or number of pieces of equipment it can control, it is actually a natural extension for the robot position and a tracking camera to be coordinated. This capability was demonstrated in the 1992 Hanford demonstration.

4.3.1 e Synopsis

Good camera placements and end-point tracking control systems can significantly improve the operability of the system and reduce operator fatigue. Stereoscopic systems are not as mature, but seem to show the best utility in precisely the unstructured situations with marginal viewing which are expected in at least some of the tanks. Thus STV should also be pursued.

4.3.2 Other Sensing Capabilities

A key objective of incorporating sensory information is to give the operator the maximum amount of useful information about the remote environment in which the telerobotic system must be manipulated. The degree of fidelity of the information displays and control outputs for teleoperation is sometimes called telepresence, and the greater the fidelity of useful displays and controls, the higher the telepresence.

Displays and control stations should also be formatted to match the operator's level of control, e.g. the displays most appropriate for teleoperation are not necessarily the most appropriate for high-level supervisory control. Judiciously applied, higher telepresence can relate directly to better operator performance. Other sensors that provide information to the operator include auditory sensing (binaural localization and spectral response), resolved force sensing (muscular force), tactile or touch sensing, and vestibular sensing via a motion platform (Sheridan, 1992).

Another key objective is accomplished by integrating sensory information from multiple sources in the telerobotics feedback control loop. By doing so, the telerobotics systems are made more flexible and adaptable to a changing environment. Having a sensory-based system allows quick adaptation to evolving requirements for unknown tasks, successful recovery from task failures, and reaction to sudden changes in the environment. Non-contact information is provided by sensors such as ultrasonic, laser range finders, infrared and structured lighting systems. To give real time feedback to the telerobotics control system provides critical information about the remote environment that can then be used to update and maintain the accuracy of the simulated world model. By doing so, course modifications can be made to react effectively to the changes and eventually succeed in accomplishing the manipulation goal. The sensory systems that appear to be most relevant to waste retrieval applications are discussed in the following sections.

4.3.2 a Proximity Sensing

Proximity sensing allows the sensing of nearby objects without visually seeing them or touching them. Commercial electromagnetic or optical systems can be used for measuring proximity (close-in ranging) to avoid obstacles or to decide when to slow down in approaching an object to be manipulated. Such a system was built for experimental evaluation in space applications (Bejczy, 1980).

Short-range sonar, commonly used in photographic ranging, can also be used. The sensor information could be displayed graphically or by sound patterns. In waste retrieval applications, proximity sensing will enable tools to maintain a fixed distance from a surface for operations such as cutting, surface following, or surveying.

4.3.2 b Force Sensing

Force sensing is used to determine the net reaction force and torque acting on a member or the resultant of component forces and torques of a member acting on the environment. In the first case, a force reflection input device-manipulator input device is typically used. This capability is discussed in a prior section. In the latter case, force-sensing or force-activated switches can allow the robotics arm to perform contact operations ranging from locating a surface to more dexterous operations in contact with the surface. For waste retrieval activities, this sensory capability will be useful for cleaning structures with load limits such as the tank walls or in-tank structures.

4.3.2 c Touch/Tactile Sensing

The movement of a touch or tactile sensor used to explore some portion of a remote environment, or to achieve touch identification of one or more objects and their positions/ orientations is referred to as pure active touch sensing. This method of sensing attempts to correlate kinesthetic sensation to infer patterns (of environment or objects) in time and space relative to the environment.

The problem with the research and development being done to date is that the basis is centered around a world of objects whose shapes are completely known, but whose orientations and positions are unknown. Not much research has been accomplished on assisting an operator to recognize objects or their orientation in an unstructured, constantly changing environment such as a waste tank. As the commercial game and toy industry moves into the tactile sensing development area, more applicable technology will be available. This development is expected within the next five years. There are a few commercial devices (the Lord Corp. is a primary vendor) known as touch-sensing devices. Such devices consist of relatively coarse arrays of magnetic, resistive, capacitive, or optical continuous force/displacement elements. These elements are placed on the telerobot at gripping surfaces and at points where obstacle collisions are likely to occur. Sensory information is sent back to the robotics control system indicating force levels and at what angles the forces are occurring. This information is then utilized by the control system, or the operator, to determine the next course of action. This technology is well understood, but is probably not appropriate for the waste retrieval process since the advantages are small and actual deployment on the retrieval system is presumed to be difficult.

4.3.2 d Other Non-Contact Sensors

Other commercially available non-contact sensors, including ultrasonic, laser range finders, infrared, and structured lighting systems, provide feedback to the telerobotics control system yielding information about the remote environment that can be used to update and maintain the accuracy of a graphical model. The information acquired by these sensor systems is generally not acquired real time, but much development is on going to speed up the acquisition time.

RTDP is assisting commercial vendors to improve their ability to acquire and integrate robotics control systems. For more complex work cells or systems, advanced features may be required, e.g., pose query and other calibration tools for maintaining accurate world models. The techniques and sensors used will be specific to the needs of a given system, the application, the requirements and the practicality.

The ability to integrate non-contact sensor information regarding the external environment with graphical programming is becoming more accessible from the commercial market. New commercial hardware allows video and sensor-generated images to be mapped onto surfaces to let an operator more accurately monitor and command a telerobotics system to move closely to objects requiring inspection. Volumetric-based radiological and chemical data can now be mapped onto surfaces to assist the operator in locating hot spots, or be mapped onto critical parts of the telerobot to help the operator minimize doses to those parts. Ground penetrating radar and other data can now be mapped onto planes so that an operator can move through a graphically defined model to located buried objects or better understand the remote environment. This type of sensor interfacing will greatly improve the operator's ability to manipulate the telerobot in a remote environment based on information that would have otherwise been invisible.

4.3.2 e Synopsis of Sensor Applications

Combined sensor integration and sensor control will be critical to performing semi-autonomous, in-contact operations in the underground storage tank system (McDonald, 1993). As demonstrated by SNL, cutting and removing in-tank hardware without disturbing the structures attached to the hardware requires integration of the graphically modeled workcell and continuous sensor data. In this demonstration, a structured lighting sensing system collected data and updated the graphics world model. Then, the operator decided what operation to execute, e.g., docking the cutting tool to the in-tank hardware. The operator approved the simulated motion and executed the cutting motion after the docking was complete.

Coupling sensors with the graphical control enabled this previously tedious task to be executed semi-autonomously in a few minutes. This ability to integrate non-contact sensor information has a direct bearing on operator efficiency and performance and on effectively meeting the retrieval functional requirements set out by EM-30.

4.3.3 Obstacle/Collision Avoidance

A sensor-based obstacle/Collision Avoidance (CA) system detects changes in the workcell (e.g., new or moved objects) and provides this information to the telerobotics controls system. With this information, course modifications can be made to react to the changing workspace. Speed is a limiting factor with a pure sensor-based CA system.

4.3.3 a Sensor-Based Obstacle/Collision Avoidance

Many researchers have investigated the use of physical sensors (sonar, ultrasound, various proximity sensors, infrared, etc.) as the primary method of real-time CA.

This work has met with limited success (Sun and Lumelsky, 1992; Borenstein and Koren, 1988) because pure sensor-based CA systems have a couple of problems.

- First, providing whole-arm sensing requires a large number of sensors on the telerobot, decreasing the telerobotic payload lifting capability and representing a significant sensor fusion problem. When there is a large amount of sensor data acquisition, a severe demand is placed on the system's computational capability and signal processing capability.

- Second, the types of sensors capable of providing high-resolution (<30mm granularity), such as laser range finders, binocular vision systems, are currently too slow for real-time computation.

While the technology is currently not mature enough for "stand-alone" utilization, it could be coupled with other controls such as a model-based system that limits speed when near an obstacle. In the TWS system, the sensors could help plan a soft contact for cleaning.

4.3.3 b Model-Based Obstacle/Collision Avoidance

A model-based collision avoidance system uses a computer description (e.g., a CAD-based model) of the remote workcell or environment. CA is achieved by comparing the telerobotic positions to known positions of other static objects in the workspace. This information requires an accurate matching of the world model to the actual remote workspace. The model-based CA adds no weight to the telerobotic arm, and its precision is limited only by that of the most sophisticated off-line modeling methods.

There are three basic approaches to model-based CA. The first maps Cartesian workspace objects into the telerobotics configuration space, looking for possible collisions. The second uses a neural network that learns how to solve the robot's inverse kinematics while avoiding outputs that create collisions with workcell objects. The third approach assigns a retarding potential field to known workcell objects. As the telerobot comes closer, the telerobot feels a stronger repulsive force thereby avoiding collisions.

This model-based CA is usually coupled with graphical control to warn the operator of motions that would cause near collisions and to prevent motions that would cause collisions. In cases such as cleaning the inside walls of the SSTs, where contact between the robot and the workcell may be necessary, the collision avoidance would be overridden; and the operator (or control system) would use other controls or parameters suitable for that particular sub-task.

Several commercial vendors have made use of the research and development conducted by universities on model-based CA and have created reliable robot motion analysis tools (collision avoidance, near miss detection and minimum distance analysis) that can be used to determine whether the telerobot will collide with or come dangerously close to known obstacles (Strenn, 1993).
Model-based CA is a relatively mature technology, and can significantly improve the safety of robotic or telerobotic operations. The open development issue is the need to keep the model current in the face of a changing environment, as would be expected within the tanks during retrieval.

4.3.3 c Coupling Model-Based with Sensor-Based Obstacle/Collision Avoidance

In reality, a hybrid CA system coupling both sensor- and model-based capabilities is the most effective. The model-based system does most of the work in providing whole-arm CA, while the sensor-based system detects changes in the workcell (e.g., if objects are moved or new objects are introduced into the workcell). Sensor-based CA reduces the accuracy requirements for performing telerobotic tasks. Model-based CA always contains some inaccuracies. For operations that require robotic manipulations in free space, the robotics program can usually overcome model inaccuracies with adaptation algorithms, but in other applications that require the robotics arm to come in contact with objects in the workcell, model-based CA control alone cannot be used. Here, sensors must be integrated by the robotics system's low level controller to accommodate the inaccuracies in the world model.

In the underground SSTs, the workcell will require extensive updating after each cycle, or run, because of the dynamic changes that will occur as a result of the waste retrieval progresses. Updating and maintaining the accuracy of the simulated world model and the model-based CA system can be accomplished by scanning the workspace with non- contact sensors (ultrasonic, laser range finders, and structured lighting) and importing that data into the graphics-based world model. Other advanced sensory feedback systems, including non- contact probing, computer vision, and chemical and radiological environmental sensors, can also be integrated as required by the process. Incorporating obstacle/collision avoidance will enable the operator to conduct more complex and tedious tasks with the assurance of not unintentionally damaging the telerobotics system or in-tank equipment. This improvement in itself will increase performance and reduce risks for many waste retrieval operations.

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5.0 PERFORMANCE EVALUATION

The RTDP has been commissioned to make robotic systems that can accomplish the waste retrieval mission faster, safer, better, and cheaper than existing manual technology. The practical question remains how these qualitative goals will be measured. The metrics to be applied in selecting potential technology approaches are faster, safer, and cheaper.

Faster — To minimize the potential for environmental damage, we must reduce the time required to remediate the waste sites. The following actions will contribute to faster clean up times:

- Implement faster operating systems which reduce site clean up times
- Reduce maintenance time
- Reduce operator training time, by implementing easier to use systems
- Reduce technology development time to meet aggressive waste clean up schedules.

Safer — Advanced technologies must reduce the hazards associated with waste cleanup by

- Limiting operator work in hazardous environments,
- Preventing equipment hazards such as collisions,
- Enhancing the enforcement of safe operating procedures.

Cheaper — Advanced technology enhancement efforts must reduce life cycle cost for site remediation by

- Reducing the capital costs of the waste clean up system (robotic and other equipment comprising the waste clean up system)
- Reducing the operating costs of waste remediation systems
- Reducing the maintenance costs for waste remediation equipment
- Reducing the costs of operator training
- Reducing technology development costs by developing broadly applicable approaches that allows development costs to be spread across many potential applications.

The Tri-Party Agreement (TPA) places a time limit on the clean up of the waste from the Hanford tanks where work on the first tank (C-106) is scheduled to begin in 2002. According to Kreig *et al* (1990), waste from additional tanks will then be retrieved as the closure process of the remaining tanks begins. The total number of tanks to be closed after the demonstration has not been determined. Nevertheless, to achieve the schedule, it is quite certain that a number of retrieval systems will need to be in operation simultaneously.

This section will quantify costs of the retrieval system and show how even small increases in speed or efficiency can result in large cost savings. The primary tangible cost savings occur when an increased efficiency can reduce the number of retrieval units required. This factor alone shows a significant benefit for the robotic control enhancements.

5.1 Cost of Robotic Arm-Based Retrieval

Westinghouse Hanford has made several cost estimates for different types of retrieval approaches (Squires, 1991) (Hennel, 1991) (Wallace, *et al,* 1993). These studies include cost estimates for the total project and for two retrieval systems: past-practice sluicing and an arm-based system.

Sluicing is the baseline approach to removing the bulk of the material from C-106. It is anticipated that a heel 1-2 ft deep will remain in the tank after sluicing is complete. The arm-based system will be used to remove the heel.

Table 1 (Squires, 1991) itemizes the total project costs for sluicing for tankC-106. The general costs itemized in Table 2 include the sluicing retrieval system at a cost of $22.1 million. The arm-based system is specifically excluded from these cost estimates.

Item	Expense $	Capital $
Engineering Studies	400,000	
Functional Design Criteria/ Conceptual Design	3,000,000	
Safety Documentation, Environmental Documentation and Reviews	4,700,000	
Retrieval System	22,100,000	
Tank Modifications	47,900,000	
Utilities/Support Systems	20,400,000	
Waste Transfer System		5,300,000
Test Facility	200,000	11,600,000
Startup and Operations	15,500,000	
D&D	11,800,000	
Project Management	10,000,000	1,200,000
Totals	136,000,000	18,100,000

Table 1. Total Project Costs

The cost for an arm-based retrieval system has been estimated separately in other sources. Hennel (1991) has prepared a rough order of magnitude (ROM) of costs for three robotic arm-based retrieval systems. Since only a ROM was required, no details of the robot system were listed in Hennel (1991). A total fabrication cost of $18 to $22 million was estimated, with the robot representing 8 to 18% of the total fabrication costs. In every case the two-story support frame was the most expensive item, and other items such as the material elevator and control trailer were more expensive than the robot system.

RTDP has performed viability demonstrations using supervisory graphics-based on-line programming of complex robotic systems as demonstrated at Hanford (Christensen 1990, 1992). The cost for equipment and commercial software has been estimated in Table 2.

Table 3 lists the basic hardware and commercial software required to enhance a robot system to enable it to have graphical supervisory control. A second price list was also estimated that included faster computers and a second workstation and totaled about $250,000. So a reasonable range of costs for the hardware and commercial software needed for graphical supervisory control is $134,000 to $250,000.

Number	Item	Price ($)
1	Silicon Graphics Indigo 2 Extreme	30,000
1	IGRIP software	60,000
1	VxWorks Developers License	22,000
4	VxWorks Target License	2,400
1	VME Bus and Power Supply	4,700
1	Force CPU-30, 68030 & Ethernet	3,500
3	Force CPU-33, 68030	7,500
1	Industry Pack Carrier	600
2	IP parallel interface	400
1	Intelligent Serial Interface	1,800
1	VME bus controller	1,500
	Total	134,000

Table 2. Estimate of Cost for Equipment and Commercial Software

The system described above used software developed by the RTDP, and it was demonstrated in 1991 and 1992 at Hanford. Some software required for the demonstration is not yet commercially supported, but RTDP software has been used throughout the DOE complex and has been and continues to be transferred to the

U.S. industry. The link between the graphics modeling package, Deneb Robotics' IGRIP, and the robot controller developed by the RTDP team, for example, was transferred to Deneb Robotics, Inc. It is now a commercially supported product. Other robotic software companies have now developed similar capabilities (Holliday 1993). Communications software between the graphical supervisory software and the robot and other subsystems was also developed for the DOE RTDP efforts.

Commercial industry has also expressed interest in this approach; some are interested in transferring the technology or developing these capabilities. It is highly probable that the capabilities demonstrated by the RTDP will be fully available in commercial products within a few years — well in time to meet the needs of the robotic arm-based retrieval system in 2002.

The teleoperational system configuration defined in Section 2.3 is kinematically controlled, and consequently already includes many of the inherent features necessary for robotic control. Although the underlying functionality is present, there may be a small cost to ensure that the system is extendible; that is, to ensure that the system provides an interface that allows an external system to read the robot positions and command motions. If the system is designed (or specified) to be extendible, the additional equipment listed in Table 2 is essentially all that is required to provide supervisory and graphical control. The point is that the additional life cycle costs to go from an end-point controlled teleoperated system to a (basic) telerobotic system are less than 0.5%.

5.2 Benefits of Robotic Arm-Based Retrieval

This section presents the benefits of speeding up the system and the subsequent impacts on life cycle costs.

5.2.1 Number of Arm-based Retrieval Units Required

There are strong economic incentives to increasing the speed of the retrieval process. Total costs related to it are substantial, while increases in speed can reduce the time required to remediate a specific tank. If system retrieval rate is increased, fewer systems operating in parallel may be required to meet the TPA milestones. This section shows that several units will be required to clean up 100 tanks in a decade, and the exact number of units required will depend upon the speed of the retrieval system.

Kreig *et al* (1990) report that a robotic system with associated waste handling system and structures may require 16 months to extract the waste from one tank.

The 16 months is the sum of two months for setup and installation in/on the tank, six months for waste retrieval operations, four months to remove the waste retrieval unit from the tank, and four months to service the unit in a maintenance facility after each extraction operation. Only six months of the 16-month retrieval cycle is devoted to the waste extraction process. It was assumed that robotics will only influence the waste retrieval process; thus, for cleaning 100 tanks in a 120-month period,

$$N = (100 \text{ tanks} / 120 \text{ months}) \times T \times 1.2 + 1 \qquad (1)$$

where:

- N = the number of units required,
- T = the time (months) required for one unit to close a tank (cannot be less than 10 months),
- 1.2 = a factor to account for spare units (Kreig uses 4 spares for 20 units), and
- 1 = a single unit added as a mock-up for trouble shooting as suggested by Kreig.

If T is 16 months, 17 units are required. We avoid non-integer values in the equation by rounding the number of units to the next higher integer. Notice that when N is 17 units, one unit is for troubleshooting, 13.3 are operating units, and 2.7 are spares. Fractional units are interpreted as averages. Sometimes 13 units are operating, sometimes 14 units are operating, but the average is 13.3.

A potential difficulty with this equation can be explored by assuming it takes exactly 16 months to close each tank. At the end of 112 months, 93 tanks will have been closed using 13.3 (average) operating units. Seven tanks will remain to be closed in eight months. Seven units will be applied to the remaining seven tanks while the other units remain idle. In this scenario, we would not meet our schedule because closing the last seven tanks would take 16 months, not the eight months remaining. To avoid additional units, we assume that units can be scheduled so that none, except for spares, are ever idle. This arrangement may be possible because not all tanks require exactly 16 months for closure. Some will require more time, some will require less, with an average of 16 months. Variation in tank closure time and appropriate scheduling can reduce the number of units required assuming that no operating units are ever idle.

We assume that two types of control are available to a robotic unit: teleoperation control and computer control, and that the baseline unit is teleoperated. Some tasks can be performed faster using teleoperation, and others can be performed faster using computer control. Adding computer control to a unit and using it when it is the faster option will speed up the waste retrieval process. We define a speed ratio to be the total time required using a teleoperated unit divided by the total time required using a unit to which computer control is added. A speed ratio of two means that using computer control will allow waste removal to be twice as fast and require half the time as a baseline teleoperated unit. Table 3 shows the number of units required to clean 100 tanks in a 120-month period with speed ratios treated as a variable parameter. These specific speed ratios were used because they result in an integral number of units.

Speed Ratio	Time to Complete One Tank (Months)	Units Required
1.0	16	17
1.2	15	16
1.5	14	15
2.0	13	14
3.0	12	13
6.0	11	12
Infinite	10	11

Table 3. Number of Arm-Based Robots Required for Waste Extraction from Hanford Single-Shell Tanks

Twelve units are the fewest that can be used. Speed ratios above 6.0 will move the time required to complete one tank closer to 10 months (the minimum required for unit installation, removal, and service), but will not further reduce the number of units required.

5.2.2 Speed Ratio Estimates

The main uncertainty in this study is the amount of time that can be saved using computer-control. For the purposes of this study, the speed ratio will be treated as a parameter.

The speed ratio must account for the time that cannot be reduced by computer control. For example, suppose the six-month extraction time comprises two months of non-operation time to analyze samples and plan extraction strategies, two months of operations for which teleoperation is fastest or most effective, and two months of operations for which computer control is fastest. If computer controlled operation is two times as fast as teleoperation for those last two months, total extraction time can be reduced from six months to five months. The overall speed ratio is 1.2 even though the speed ratio for the specific tasks performed is 2.0.

Most available information on speed ratios compares teleoperated robotic systems to humans. Table 4 summarizes some of the available information. Strictly speaking, the data is given as time ratios, rather than speed ratios, but the columns have been "inverted" so that the result is a comparable speed ratio. For example, the first column indicates that a certain task took 3.6 times longer when performed teleoperationally than when performed with a computer-controlled robot (telerobotically). This calculation implies a speed ratio of 3.6 for telerobotic control.

Reference	Teleoperation / Computer	Human / Computer	Teleoperation / Human
Hannaford: - Force feed back - No force feed back			 5.2 7.5
Kring & Meachum			8
Drotning and Griesmeyer	3.6	1.6	2.2
Bartilson *et al*		1.5 to 2.3	

Table 4. Robotic and Human Time Ratio Comparisons

The Hannaford (1989) information is a composite of several experimental tasks including attaching Velcro fasteners, placing pegs in holes, and connecting various electrical connectors. Kring & Meachum's (1988) data is a composite from several sources compiled at ORNL. Drotning and Griesmeyer's information (Drotning and Griesmeyer, 1989) comes from a study on spent nuclear fuel transportation, which gives time estimates for unloading spent-nuclear fuel casks. The Bartilson *et al* (1984) information is for automated maintenance in nuclear power plants. They estimated 36 hours were required for humans and 16 to 24 hours for computer controlled robots to complete a cavity cleanup.

While these applications do not exactly correspond to extracting waste from Hanford tanks, the limited data suggests that humans work faster than teleoperated manipulators, and that computer-controlled robots may work slightly faster than humans if special tools and clothing are required to carry out an operation. This information implies that computer controlled robots will perform the same tasks faster than teleoperated robots. More definitive speed ratios must come from comparative experiments using tasks applicable to tank waste extraction. The RTDP has committed to building a testbed at Hanford which will assist in addressing this issue by generating quantitative data.

5.2.3 Capital and Operating Costs

Using the costs of the robotic system outlined in Section 5.1, we will use a baseline unit cost of $20 million for the arm-based retrieval system, plus $250,000 for computer (graphical supervisory) control, and an additional $50,000 for sensors for each unit. Software and other engineering costs (estimated to be about 2 labor-years of effort) for the computer-controlled manipulator and end effectors (using existing user-ready technology) are estimated to be about $400,000. We assume maintenance costs will be $20,000 per year for each manipulator unit and $50,000 for each computer-controlled unit.

NOTE: Development costs for technology that is not currently available would increase these costs: for example, the use of data fusion to keep a model-based graphics control system current with changes that take place as waste is removed. Although some of these costs may be borne by independent technology efforts, the need for a commitment to develop this sort of enhancement must be balanced by the projected benefit, the likelihood of success, and the alternate path that will be followed if the development does not succeed.

Krieg (1991) estimates that each teleoperated unit will require six associated technicians. We assume the same number for computer controlled systems even though the computer-controlled system will require less operator time. The computer controlled system will probably require a supervisor-operator to be present at all times, taking the place of a full-time operator. We estimate that the loaded salary for a technician will be $100,000 per year for each unit.

The process of removing a unit from one tank, servicing it, and inserting it into another tank will be very expensive for both technologies because of health, safety, and environmental protection procedures. The two systems will have the same insertion, removal, and servicing costs (except for maintenance costs as mentioned above) because both require the same number of insertions and removals (one per tank). It will be assumed that the same number of units are being serviced at any time. Four months is required to service a unit after closing each tank for a total service time of 400 unit months. There are 3.33 (average) units being serviced at any given time (400 unit months/120 months). The number of units being serviced does not depend on speed, but on unit servicing time, total project time, and the number of tanks. The costs associated with insertion, servicing and removal should be similar for the two systems, so that they do not influence the calculation and they have been neglected.

Supervisory computer controlled units will require sensors and associated hardware (metal detectors, proximity sensors, and topological mapping systems). It is conceivable that this hardware may require radiation hardening; however, it appears that the required sensors use electrical loops, capacitors, and piezoelectric crystals which are much more radiation tolerant than semi-conductor based devices. We do not expect excessive additional sensor costs dictated by radiation tolerance requirements. Table 5 summarizes cost assumptions used in this study.

5.2.4 Results

Table 5 shows capital and operating costs for both systems. It also shows present values computed by adding capital cost to discounted operating cost. Operating

Budget Item	Teleoperated Manipulator	Supervisory Controlled Robot
Waste Retrieval Unit Capital Cost	20,000 each	20,000 each
Computer Hardware	0	250
Sensor Sets	0	50
Hardware, Software, and Sensor Engineering	0	400
Six System Operators	600/year each	600/year each
Unit Maintenance	20/year each	50/year each

Table 5. Cost Assumptions (in $K)

costs were discounted using a government discount rate of 4% above inflation and a system life of 10 years. The last entry shows a benefit/cost ratio that is the present value of system cost saved using computer control divided by the capital cost of computer control. Benefit cost ratios are also shown in Figure 12.

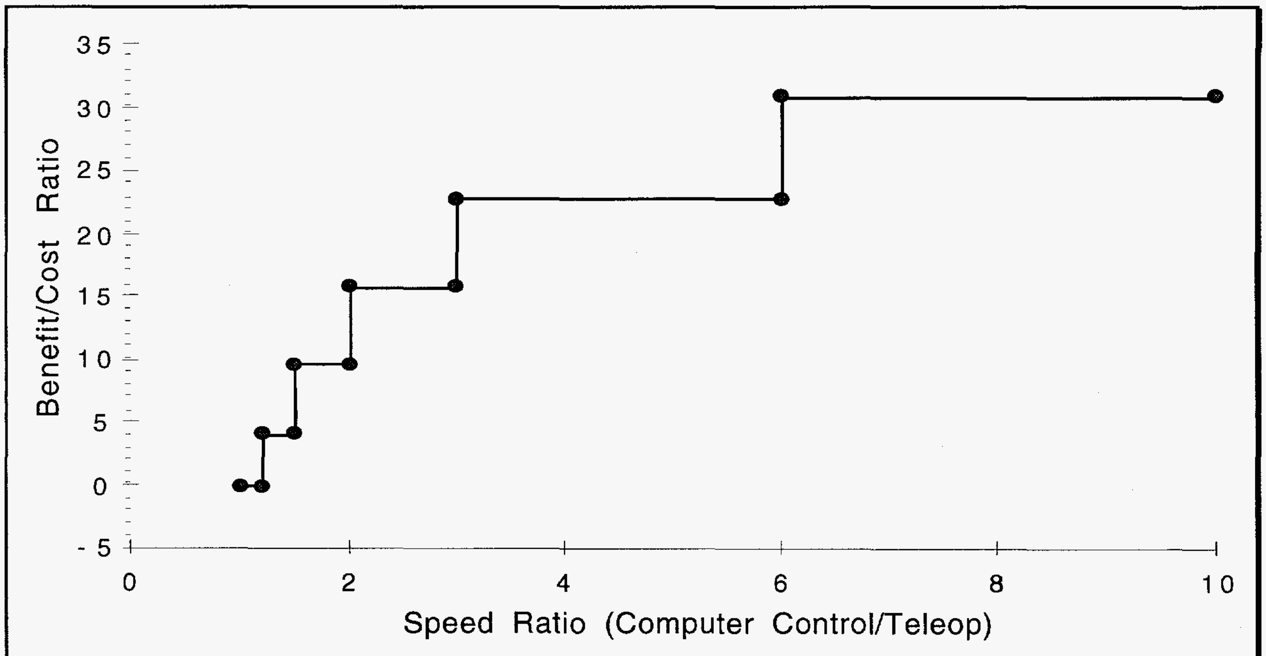

Figure 12. Benefit/Cost Ratios Hanford Storage Tank Waste Extraction

For speed ratios between 1.0 and 1.2, computer control does not reduce the number of required units, and the computer-controlled system costs more. However, as noted in Section 5.0, Introduction, the reference teleoperational system may not be adequate. At a speed ratio of 1.2, the number of units required drops from 17 to 16 and the benefit/cost ratio for computer control is 4.1. For the assumptions made in the analysis, computer control is not financially attractive for speed ratios below 1.2. It is, however, very attractive for speed ratios of 1.2 and greater.

5.2.5 Conclusions

A range of benefit/cost ratios for speeding up an arm-based retrieval system by adding supervisory-graphical based control has been illustrated. The benefit with respect to reducing the total number of retrieval systems required while retrieving the waste in the time allotted is large if the computer-controlled unit can reduce waste retrieval time by a factor of 1.2 or greater (i.e., >20% speed increase).

The assumptions made in this analysis are based on a preliminary system design and even more preliminary estimates of unit installation, operation, disassembly, and maintenance times. Although the assumptions are tentative, it is still very clear that increasing system speed has tremendous cost saving leverage because of the system's high capital cost. Since graphical supervisory control offers a speed advantage and has relatively low capital cost, it is very likely to give large benefit/cost ratios.

	Tele-Op System	Supervisory Controlled Robot					
Speed Ratio	1.0	1.0	1.2	1.5	2.0	3.0	6.0
Units	17	17	16	15	14	13	12
Capital Cost $M							
System	340.00	340.00	320.00	300.00	280.00	260.00	240.00
Computer	0.00	4.25	4.00	3.75	3.50	3.25	3.00
Sensors	0.00	0.85	0.80	0.75	.70	0.65	0.60
Engineering	0.00	0.40	0.40	0.40	0.40	0.40	0.40
Total Capital	340.00	345.50	325.20	304.90	284.60	264.30	244.00
Operation Cost $M/Year							
Operations	10.20	10.20	9.6	9.00	8.4	7.8	7.2
Maintenance	0.34	0.85	0.80	0.75	0.70	0.65	0.60
Total O&M	10.54	11.05	10.40	9.75	9.10	8.45	7.80
Present Value of Costs $M							
Total	430.94	440.84	414.93	389.02	363.11	337.21	311.30
Savings	0.00	9.90	16.01	41.92	67.83	93.73	119.64
Computer Capital	0.00	5.50	5.20	4.90	4.60	4.30	4.00
Savings/Comp Cap		-.08	4.1	9.6	15.7	22.8	30.9

Table 6. Waste Extraction System Cost.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

To meet long-term program objectives, the first generation arm-based retrieval system should be both flexible and extendible. In particular, the system should be capable of being controlled telerobotically as well as teleoperationally. While it is expected that some robotic enhancements will be necessary to meet the operational requirements, the particular features used in the control system design will be a function of the chosen system design and the proposed mining strategy. However, certain enabling features which ensure that the system is robotically controllable are so important that they should also be required. Only the reference teleoperational system is limited to a single control paradigm, and cannot accept many of the automatic control or robotic enhancements discussed. A system capable of robotics, however, provides the flexibility and extendibility required to protect the initial investment, by facilitating adjustment to emerging requirements and allowing the use of maturing technology. For example:

- System requirements are evolving, and it is probable that design adjustments may be needed to respond to late breaking changes in requirements and discoveries during the retrieval process.

- Unforeseen problems may arise with the chosen control scheme which would be less costly to correct if a "toolbox" of robotic enhancements could be applied.

- The first generation system is the precursor to the follow-on retrieval systems that will be used in completing the program and should provide knowledge and experience that can be applied toward the advanced features that will be required.

6.2 Recommendations

It is expected that the teleoperational system described in Section 2.3 will have difficulty meeting all of the operational requirements. Section 5.0 describes how the robotic enhancements are expected to pay for themselves in terms of increased retrieval rates versus numbers of systems required. Consequently, there are many reasons that the first generation system should not only be "robotics capable," but also include a number of the proven enhancements. The following sections describe the recommended enhancements. Some are so basic they should be required in a minimal system, others would be included as appropriate to the chosen design approach.

6.2.1 Minimum System

A minimum system should include both teleoperational and telerobotic capabilities. The recommended minimal system does go beyond the system discussed because some features have been deemed necessary to successfully meet the retrieval, operational, and safety goals envisioned for the most effective system. Many of these recommended technologies lean toward the ability of the system to be programmable and work with other subsystems in an integrated fashion. They also tend to make the system more versatile. Both features are considered to be extremely important in this first of a kind system.

The overarching technology is an open architecture supervisory control system, because it allows this versatility and expandability and it is required for many of the additional supporting technology enhancements. It is an enabling technology, which can take on various subsets of the other described enhancements, increasing the level of automation. The supervisory control and open architecture of the controller reduces risk by allowing future technology enhancements to be integrated into the system as necessary to complete retrieval or as desirable to enhance performance. The following readily available, proven features should be included:

- End-Point Control (See Section 4.1.1)

End-point-controlled systems allow the human operator to control the movements of the arm's end effector, rather than specifying movements of individual joints. End-point control is a mature technology that significantly improves controllability of the manipulator and is routinely employed in commercially available telemanipulators. This capability has been included in the reference teleoperational system described in Section 2.3.

- Accuracy, Responsiveness, and an Open Architecture Suitable to Allow Future Addition of Any Telerobotic Enhancements (See Sections 4.1.1, 4.1.4, and 4.2.5)

Responsiveness, as described here, is the ability of a manipulator to reproduce the input device's trajectories and impedance in time and space. The optimal machine accepts forces/movements and converts them to acceleration/position without modifying or constraining the input. Accuracy and responsiveness are measured by several key parameters: position control, velocity control, and acceleration.

The accuracy of the manipulator system needs to be sufficient to allow contact operations with the tank, risers, and waste. With a regulatory requirement that imposes a 99% removal of the waste, a heel of less than 1/2-inch is all that would be allowed to remain on the cylinder walls and floor in the cleaning of a full tank. Further, the candidate hydraulic end effectors require a positional accuracy of less than an inch. This dictates that the minimal system must have accuracy and repeatability of less than an inch.

As described in Section 4.1.4, Responsiveness, it is preferable for the system to be user-paced, which dictates a desirable acceleration bandwidth above 9 Hz. The constraints of the physical manipulator geometry, such as those imposed by the riser diameter for insertion of the manipulator, may force some compromises on the acceleration bandwidth. A high bandwidth is most desirable.

Sufficient accuracy and responsiveness of the manipulator are important for both teleoperation and telerobotic control. Many of the technologies described below, such as teach and repeat, collision limiting, and force feedback, for example, require that the robot system be accurate and responsive.

- Ability to Allow Future Addition of Any Telerobotic Enhancements (See Section 4.2.5)

Many commercial vendors are working to enhance their current control capabilities. These vendors are pursuing flexible and versatile open architecture control platforms, with multimode control and real-time monitoring of internal and external environments. This movement points out the need to keep our options open and to be able to incorporate the new technology as it becomes available.

By its modular and expandable nature, a robotic system that has, or at least allows, supervisory control provides the best posture for enhancement and is necessary for reduction of risks associated with the arm-based retrieval system. The supervisory control and open architecture of controllers reduce risks by allowing future technology enhancements to be integrated into the system as necessary to complete retrieval, or when desirable, to enhance performance.

- Operator Visualization Suitable to Implement the Selected Mining Strategy, which May Include Enhanced Video Imaging or Graphical World Modeling (See Sections 4.2.2 and 4.3.1)

Graphics-based simulation systems allow the operator to manipulate a graphical representation of the manipulator and modify intended movements *before* they are executed by the manipulator. This type of programming allows a robot to be programmed more rapidly and safely than if programmed by line-by-line coding or trial-and-error.

Accurate graphical modeling requires advanced vision and sensing capabilities, to provide an accurate image of the tank interior. Primary emphasis is on volumetric representation, obtained by *a priori* engineering data and geometric sensors. This has been a rich area for recent technology advances and is reflected in a variety of available sensors. Graphical based programming and a means to update the robots graphical world model as the robot alters its environment are recommended.

- Force Feedback, or at least a Visual Display of Forces (See Section 4.1.2)

Force feedback is an important supplementary sensory channel. Force feedback may be provided in a number of ways; extensive research has identified advantages and disadvantages for implementation of and reliance on each method. Visual displays of force offer an inexpensive implementation of force feedback, but are often difficult to interpret and may increase demands on the operator.

Force based control will reduce the risk of damaging retrieval equipment and the tank itself. The minimal system should be capable of sensing and displaying tool tip forces.

- Teach and Repeat Capability for Programming of Routine Operations (See Section 4.2.1)

The ability to program repetitive tasks ensures safer, faster operation and greatly reduces the demands on the human operator. "Teach and repeat" capabilities can be implemented through low-level or supervisory control, using the same user interface and the same input device as the reference teleoperated system, with the addition of a terminal or teach pendant to record points, paths, or programs. It is unlikely that a system lacking this capability can meet the performance requirements of the waste retrieval task.

- Collision Limiting, to Include Limiting of the Forces that can be Applied during Contact (See Section 4.3.3)

The forces generated by impact or collision of the manipulator hardware with the tank, in-tank hardware, or with other parts of the arm or manipulator itself may be limited or prevented by several means. The arm can be equipped with joint limits, to prevent extension into the tank surface, or with velocity limits to limit the maximum force generated by the arm. Either of these methods also limits the performance of the manipulator, resulting in undesirable trade-offs in performance. Joint limits are impractical for accommodating the variety of obstructions imposed by in-tank hardware. More advanced collision avoidance systems may employ sensor capabilities (e.g., sonar, ultrasound, or proximity sensors) to inform the control system of changes in the tank environment, and respond accordingly. Model based collision avoidance that uses the physical geometries of the robot system and tank environment can be effectively used for obstacle avoidance of known (i.e. modeled) objects.

Model based obstacle avoidance is recommended for the minimal system. This alternative will ensure that the robot system does not impact modeled objects in the environment. The use of model based collision avoidance also allows remediation action to occur before contact with the obstacle. For example, the robot system could be slowed down as it approaches an object in the workcell. Unknown objects in the environment will need to be avoided by using sensor based methods. This practice is recommended for the minimal system; however, it should be noted that performance of the sensor in the tank environment and the relationship between arm performance (the distance it takes and arm to stop, for example) and range of the sensor must be considered during design.

6.2.2 Additional Features that may be Required

Depending upon the system design, mining strategy, and other operational considerations, additional features may be necessary to provide a fully functional system with appropriate safety features. While not fully mature, these enhancements represent significant potential gains and could be developed with minimal risk of failure. Some of the enhancements which could be added to a "robotics capable" system are:

- <u>Force Reflection</u> (See Section 4.1.2)

Force reflection, a form of force feedback, is a commercially available technology (albeit on smaller robots and manipulators) that enhances the operator's ability to perform complex teleoperational tasks, particularly those involving control of forces. The greatest advantages of force reflection are realized when manual task components require guidance or delicacy in areas that are difficult to see with remote television cameras, or when viewing is hampered by dust, gases, or other obstructions. Force reflection can be applied to the whole arm or just critical joints depending on the application. For example, tool tip force reflection would require sensors only in the wrist area.

The option of force reflection appears to be desirable, but may need to be investigated further to determine the true cost/benefit. Other options such as model based (virtual) force reflection should also be considered because it has an inherent advantage over sensor based force reflection of not requiring joint force-torque sensors. The use of model based force reflection seems to be an appropriate means of reflecting important forces back to the operator and should be pursued as this technology becomes more widely available.

- Graphical Programming with Model Update (See Section 4.2.2)

Graphical programming allows the operator to observe collisions and lock out hazardous motions through simulation *before* issuing commands to the manipulator. Graphical programming can contribute significantly to the safety and speed of robotic operations and is recommended, especially as it appears that this technology are becoming increasing available through commercial sources.

- Sensor Based Control (See Section 4.2.3)

The robot's world model can be extremely useful when non-contact operations are performed. When contact of the robot with the environment (including operations that require a precise standoff distance from the surface) are required, the geometric models are not precise enough for these contact operations. The inaccuracies of the world model can be compensated with sensors. It is envisioned that the robot will need to interact with the environment during the retrieval tasks and sensors will need to be used for the precise control of the robot system.

- Increasing Telepresence through Sensor-Based Operation (See Sections 4.3.2.1 and 4.3.2.2)

A key objective of incorporating sensory information is to give the human operator the maximum information about the remote environment. High-fidelity information displays and control outputs relate directly to increases in operator performance and should be incorporated whenever practical. New and emerging technologies that increase telepresence are a thriving area in many industries (not just robotics). It is very likely that advances on these fronts will continue to have a favorable impact on increasing the operator's telepresence and thus performance.

- End-Point Video Tracking (See Section 4.3.1.4)

Real-time visual tracking of robotic motion, or automatically aiming cameras at the tool work location, using commercially available hardware is easily achievable. Automated tracking using remote cameras frees the human operator from this time-consuming task, and allows the operator concentrate on teleoperation of the manipulator. Because a supervisory controller should not be limited in the type or number of components it can control, coordination of visual tracking with robot position is a natural extension of the advanced control systems. This option is recommended and should be a function of the supervisory control system.

- Stereoscopic Vision (Robotic capability is not required.) (See Section 4.3.1)

Because it provides more visual information to the operator, stereoscopic vision is believed to offer advantages over mono-image television. The precise relationship between stereoscopic vision and performance has not been quantified. Although stereoscopic viewing may not improve overall task completion time, it is likely to increase safety by increasing the ability of the operator to accurately position the manipulator when operating in manual control and may also reduce operator fatigue.

6.2.3 Features not Recommended for this System

The following technologies are eithernot sufficiently developed, or do not seem to have significant benefit for the retrieval task.

- Touch/Tactile Sensing

This method of sensing attempts to correlate kinesthetic sensation to patterns of environment or objects in the manipulator's work environment. Such devices require complex arrays of sensors to allow the operator to recognize objects or their orientation in an unstructured, constantly changing environment such as a waste tank.

- Fully Automatic Autonomous Control

This level of control is at the extreme end of the control continuum and would require significant advances in artificial intelligence to be of practical benefit. In the near term, this alternative does not seem practical for the retrieval system.

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