ROBOTICS SCOPING STUDY TO EVALUATE ADVANCES IN ROBOTICS TECHNOLOGIES THAT SUPPORT ENHANCED EFFICIENCIES FOR YUCCA MOUNTAIN REPOSITORY OPERATIONS

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ABSTRACT

This paper presents an evaluation of robotics and remote handling technologies that have the potential to increase the efficiency of handling waste packages at the proposed Yucca Mountain High-Level Nuclear Waste Repository. It is expected that increased efficiency will reduce the cost of operations. The goal of this work was to identify technologies for consideration as potential projects that the U.S. Department of Energy Office of Civilian Radioactive Waste Management, Office of Science and Technology International Programs, could support in the near future, and to assess their "payback" value. The evaluation took into account the robotics and remote handling capabilities planned for incorporation into the current baseline design for the repository, for both surface and subsurface operations. The evaluation, completed at the end of fiscal year 2004, identified where significant advantages in operating efficiencies could accrue by implementing any given robotics technology or approach, and included a road map for a multiyear R&D program for improvements to remote handling technology that support operating enhancements.

INTRODUCTION

Oak Ridge National Laboratory's Remote Systems Group was asked to do an evaluation study by the U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM), Office of Science and Technology and International Programs (OST&I), to assess robotics and remote handling technology improvements. The purpose was to identify technology improvements that could enhance operating efficiencies at the proposed Yucca Mountain (YM) High-Level Nuclear Waste Repository [1]. The evaluation was started with a review of the YM repository baseline design available in the literature, and meeting with design staff for above- and below-ground operations. This established a basis for assessing the value of implementing robotics and remote handling technology advancements. The above-ground facility requirements and the procedures for handling spent nuclear fuel (SNF) casks were examined by considering SNF acceptance, unpacking, sorting and storage, repackaging including welding, inspection, and decontamination. The below-ground facility requirements and procedures were examined to understand the operations for transporting SNF packages to their storage locations in the drifts, as were the monitoring requirements for waste packages and drift parameters. From this evaluation, recommendations were made to implement or expand the use of various robotics and remote handling technologies, and modifications or changes for improving operating efficiencies were suggested. The improvements in efficiency were measured by their ability (a) to reduce handling time, thereby increasing the throughput of waste packages; (b) to reduce personnel exposure that has the potential to reduce the size of the operations staff; and (c) to recover efficiently from unforeseen events. Each of these improvements has the potential to reduce the cost of operating the facility.

An overall multiyear robotics development program was outlined that supports improved efficiencies for cask handling, cask and drift (tunnel) inspections, data collection, incident recovery, and surveillance and inspection. DOE currently funds several universities in the area of robotics research. This work examined existing technology programs in place at universities, as well as at government laboratories and industry, and identified those that are relevant to improving operations at the proposed YM repository.

The output of this work was a robotics and remote systems technology development, multiyear road map that focused on improving the operational efficiency of the Yucca Mountain repository for waste package handling and related operations. The key benefit for DOE will be the development of a tailored research program to assist in the future optimization of remote operations at the proposed YM site. By increasing the throughput of SNF casks at the repository, the potential exists to save a significant amount of money for parallel facility construction costs as well as site operations costs.

Background

YM is the proposed site for a monitored geologic repository (MGR) for disposal of high-level radioactive waste. The proposed MGR at YM is located about 160 km (100 miles) northwest of Las Vegas, Nevada. YM is a ridge composed of a sequence of tilted layers of variably welded and fractured tuffs. (Tuff is volcanic rock formed of pyroclastic material. The tuff at the YM site was formed at very high temperature and velocity, causing it to fuse into a welded tuff.) The facility will be designed for long-term storage of 70,000 metric tons of heavy metal (MTHM) consisting of commercial SNF, 2,500 MTHM of DOE-managed SNF including naval SNF, and approximately 22,000 canisters of vitrified high-level waste (HLW) [2].

Receipt of waste packages (WP) at the repository is planned to begin in 2010. Although receipt and emplacement rates are assumed to be the same, the actual emplacement rate is a function of the types and sizes of casks and canisters received. Surface staging may be provided at the repository to compensate for any differences between receipt and emplacement rates, and to provide for blending of fuel assemblies to meet the thermal limits in the drifts. (The term “drift” refers to a tunnel.)

Surface Facility

The nuclear wastes that are destined for disposal in the potential repository will be received and packaged for emplacement in a 150-acre area located near the northern entrance to the repository, the Geologic Repository Operations Area (GROA). The surface facilities at the GROA consist of those systems and components used to receive, prepare, and package the waste for underground emplacement. The operations at the North Portal are divided into two work areas: a protected area that is a radiologically controlled area (RCA) and the remainder of plant area. The operations involving radioactive materials will be conducted in the protected area, which contains, among other structures, the Fuel Handling Facility (FHF), the Canister Handling Facility (CHF), and the Dry Transfer Facility (DTF). Support operations for the GROA will be accomplished elsewhere in the facility and are not relevant to this work.

Operations of the surface facility will include receiving the shipping casks of waste and unloading them from the rail or truck transporter, emptying the packages, repackaging material in the final waste canisters for burial, moving the packages to and from the closure cell (CC), and managing any decontamination and maintenance activities necessary. These activities will be a mix of remote- and contact- handled tasks. Some of the planned contact-handled tasks can and should be done remotely for the purpose of meeting “as low as reasonably achievable” (ALARA) guidelines. Casks that can remain intact while their contents decay to acceptable thermal conditions may be stored on an aging pad, where they will be monitored for radioactive decay and temperature, and subsequently processed through the DTF. The remote operations in the DTF are typical of those in the FHF and CHF.

Subsurface Facility

The waste emplacement in the repository will be located in the Topopah Spring Member, a welded tuff unit of the Paintbrush Tuff. The potential site for the emplacement area is bounded by geologic faults, but the emplacement area itself is free of significant faults. These potentially usable areas include a primary area and an expansion area. The primary area consists of an area bounded on the east by the Ghost Dance Fault and on the west by the Solitario Canyon.

The ramps and main drifts will be 7.6 meters (25 feet) in diameter and will be used for waste transport, ventilation, service utilities, and personnel access. The North and South Ramps and the main drifts have grades of less than 3% to ensure the safe use of heavy-rail transport into the emplacement drifts.

Emplacement drifts will be 5.5 meters (18.2 feet) in diameter and will be spaced at 81 meters (266 feet) between the centers of each drift. Each emplacement drift has two sets of doors to control access. Each door will have ventilation regulators (louvers) to control the flow of air through the emplacement drift, and the doors will be remotely controlled from a surface control room. Approximately 10% of the total number of emplacement drifts will be developed prior to the start of emplacement operations. Development of the remaining emplacement drifts will be performed concurrently with waste emplacement during the repository operations phase, using two separate and independent ventilation subsystems.

The underground operations begin when a WP has been placed on the locomotive for transport into an emplacement drift. This includes transporting WPs underground and placing the WP in position. A portion of this task—moving the package underground on rails—will be accomplished with personnel operators shielded from exposure while directly controlling the locomotive equipment. Movement to place the WP in its final position in the drift (tunnel) will be managed remotely. Personnel will not be allowed in the emplacement drifts during normal emplacement operations.

Candidate Technologies

The list of "technology desires" obtained from OCRWM and presented below is a compilation of preliminary thoughts about technologies that could increase the operating efficiency for the next-generation design of the proposed YM repository. The list was used as a starting point by the investigators, but as the requirements for the repository were better understood, it became clear that although many of the 26 items would be interesting and beneficial to future YM operations, they would not all make significant improvements to operating efficiency. The list is discussed in detail below. Added items not on the original list are also discussed.

Initially Proposed "Desired" Technologies

OCRWM provided an initial list of technologies that were of potential interest for the YM facility based on their value for enhancing operational efficiency or solving difficult problems. This list proved to be a useful starting point for developing the robotics evaluation. Some of the topics listed were subsequently redefined to focus on YM improvements; many have been recommended for later funding or eliminated until the problem area that they address becomes better defined.

The initial list of desired technologies is shown in Table I. The titles have been summarized and adjusted according to the perceived original intent and the associated description, and modified to reflect discrete subjects. The table summarizes the list of desired technologies, adds priorities, and gives a brief description of issues and potential benefits.

Table I. Original List of Desired Technologies Plus Added Items

	Technology Candidate	Priority	R&D Issues	Potential YM Benefit
1	Sensor-based robot control	High	• Task automation strategies, scripting, and switching modes between human and robotic control • Automated task completion techniques • Fault recovery modes	Significant decrease in time required to complete remote systems tasks
2	Vision-based robot control	High	• Target identification and tracking • Robust real-time real-world image-processing techniques • Camera resolution vs. field-of-view limitations	Significant decrease in time required to complete remote systems tasks
3	Modular arms for plutonium operations	Low	Not relevant to YM	Not relevant to YM
4	Remote weld closure	N/A	This topic is addressed by a separate OST&I thrust	Addressed elsewhere in the OST&I program
5	Accumulated dose modeling	Medium	This is generally a remote facility baseline task; task information, not yet available, must be extensive before this topic area could be defined	Difficult to quantify payback. Funded initial study would be necessary to determine

	Technology Candidate	Priority	R&D Issues	Potential YM Benefit
6	Serpentine manipulation	Medium	YM designs are not yet specific enough to establish proper R&D constraints. Typical critical requirements include payload, reach, allowable arm cross-section area, repeatability, end-effector, and deployment requirements	Target task requires significant further specification before relevance and potential payback can be established
7	Small rail inspection robot	Medium	YM designs are not yet specific enough to establish proper R&D constraints. Typical critical requirements include payload, runtime, positioning/tracking accuracy and repeatability, sensor interfaces, and deployment requirements	Target task requires significant further specification before relevance and potential payback can be established. Other solutions already exist
8	Non-contact precision drift wall inspection sensor system	High	• Optimization of scanning for drift conditions • Database optimization for visualization and record keeping	Noticeable decrease in time required to complete survey task; significant improvement in data quality and archiving
9	In situ waste package weld inspection sensor system	High	• Identification of sensor technologies • Sensor fusion of various sensor types • Presentation and archiving of data	Significant decrease in time required to complete remote systems tasks
10	Radiation-hardened DC motors	Medium	General technology available for the most part; application specifications must be defined for each instance	Extend operating life of remote systems and reduce maintenance costs
11	Lightweight, compact, long-reach mast to carry small payloads	Medium	Target task requires significant further specification before any R&D issues could be established	Target task requires significant further specification before relevance and potential payback can be established
12	High-consequence, fault-tolerant hardware and software architectures	Medium	Suggest for the time being that current state-of-the-art techniques be applied extensively to all systems design	Application of existing state of the art brings the primary benefit of reliable systems
13	Advanced human-machine interfaces	High	• Human-robot interaction and coordination • Remote viewing optimization • Graceful failure recovery	Significant decrease in time required to complete remote systems tasks
14	Physical security robots for inspection and perimeter security	Medium	Target task requires significant further specification	Much technology exists to meet this need; application specifications must be further developed to establish a benefit
15	Operations and maintenance robots for routine and off-normal events	Medium	Target task requires significant further specification	Target task requires significant further specification before relevance and potential payback can be established

	Technology Candidate	Priority	R&D Issues	Potential YM Benefit
16	Flying/hovering robot for inspection and measurement	Medium	Target task requires significant further specification	Target task requires significant further specification before relevance and potential payback can be established
17	Conversion of gamma and neutron radiation to electricity for onboard robot power	High	Development and verification of the physics of the conversion technology	Extension of operation time for untethered remote systems
18	Long-life, no-exhaust mobile power sources for high-temperature, high-radiation environments	Medium	A worthy topic but much effort has been expended in this area with little result	Increased operation time for untethered remote systems
19	Low-power communications for in-tunnel use	Medium	Other than radiation-hardening specifics addressed under another topic, most issues relate to the baseline design (not OST&I R&D)	Improved communications (quality and bandwidth) to remote systems and sensors
20	Modeling of communications effectiveness in metal-lined tunnels containing metal objects	Medium	Most issues relate to the baseline design (not OST&I R&D). Technical experts exist to address this area	Improved communications (quality and bandwidth) to remote systems and sensors
21	Mobility over small obstacles and tight spaces for tunnels	Medium	Target task requires significant further specification	Target task requires significant further specification before relevance and potential payback can be established
22	Visualization in tight spaces with no ambient light; real-time-world model construction	Medium	• No ambient light sensor systems • Data fusion • Human-machine interfaces appropriate to task viewing	Improved viewing and visualization could decrease remote-operation task times
23	Radiation sensors to distinguish small, moving radioactive gas in the background of waste package shine or in the presence of radon	Medium	Target task requires significant further specification	Target task requires significant further specification before relevance and potential payback can be established
24	Sensor/sampler combination to characterize/collect thin films of moisture on surfaces	Medium	Target task requires significant further specification	Target task requires significant further specification before relevance and potential payback can be established
25	System to place and retrieve dust and moisture material samples	Medium	Target task requires significant further specification	Target task requires significant further specification before relevance and potential payback can be established
26	Electroactive polymer robot actuators	Low	Not relevant to YM	Not relevant to YM

	Technology Candidate	Priority	R&D Issues	Potential YM Benefit
Newly Defined Technology Items				
27	Approach for radiation-hardened, high-temperature electronics	High	• Development of radiation- and temperature-tolerant electronics family • Development of guidelines for use	Extension of operating times in hazardous environment and reduced maintenance costs
28	Dexterous manipulation	High	• Manipulator system design • Master controller concepts • Dexterous end-effectors • Remote viewing systems • Actuation, sensing, and controls • Mobility deployment platforms • Human factors optimization • Operator interfaces to enhance sense of "presence" ("being there")	Significant decrease in time required to complete remote systems tasks
29	"Design for remote" operations and maintenance optimization studies	High	Involves a complete analysis of the facilities, remote processes, target task equipment, remote systems equipment, tooling, and operating culture to produce an optimized approach to remote tasks with guidance on equipment design and remote process flow	Significant decrease in time required to complete remote systems tasks

A substantial number of these proposed items were eliminated because (1) they are not sufficiently relevant to YM, (2) existing technologies are available for direct procurement or can be built to specification (i.e., these are not OST&I R&D topics), or (3) they are too difficult to quantify with respect to return on investment at this time. The following discussion addresses relevance and other issues that determined the final applicability in the ranking of technologies. The investigators assumed that this OST&I program will begin as a small-scale effort and increase to a larger funding level over a several-year period. Therefore, the evaluation focused on the items considered to have a high impact on operational efficiencies, leading to increased throughput of WPs and cost reduction. Items that the present baseline design engineers could consider were avoided because this task addresses enhancements to future operations. One category of proposed technologies that was excluded was the one that proposed a technological solution to an unspecified or inadequately constrained YM task. Three new topics—items 27, 28, and 29—were added: radiation-hardened electronics, dexterous manipulation and remote operations, and maintenance studies.

Prioritization of Technologies

The technologies were categorized according to high, medium, and low priorities. The technologies in the high-priority group are expected to have favorable returns on investment, meaning a large impact on operating efficiency, and therefore should be funded. To a lesser degree some of the medium-priority technologies, although not expected to significantly improve operations, should be developed if funding is available after the high-priority items are addressed. The low-priority items should not be funded through the OST&I program, since they would not lead to significant operating improvements. The high-priority items are presented below.

Sensor-Based Robotics or Telerobotics

Typically, remote operations take 5 to 15 times longer than hands-on execution of similar tasks. For a facility with significant emphasis on remote operations, task-completion-time efficiency becomes a high-priority issue to address in the context of cost of operations. Conventional teleoperation is slow and impacts efficiency and plant throughput;

remote operation is also very fatiguing for the operating technician, requiring that additional operators be available so that they can swap out frequently. Sensor-based robotics and the closely related technology of vision-based or visually guided systems improve efficiency and decrease fatigue by making use of automated robotic functions to assist the operator in task completion. The sensor-guided component of this task that distinguishes it from other telerobotics-type activities is that the robotic actions would be guided by directly sensing the local task environment with minimal a priori, time-consuming world modeling. There is also a major benefit to be gained from control strategies that manage manipulation (intentional contact) and prevent collisions (unintended contact) between objects in the facility. Sensor-based task automation could manage manipulator loading and obstacle avoidance to prevent damage to the manipulator systems from overloading arms or jamming of components to be manipulated (such as fuel assemblies), occurrences that would cause serious time delays.

Definitions. Before research issues are discussed, it is useful to define the various remote systems terms as used throughout the rest of this paper.

> *Teleoperation* refers to direct human-in-the-loop control of the positioning of the manipulator (or mobility) system. All motions made by the operator are replicated by the manipulator in the hazardous environment through the use of the master controllers. This is the capability most closely associated with traditional remote systems.
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> *Robotics* refers to manipulation (or mobility) guided by a computer with no direct human intervention. The traditional definition dictates preprogrammed repetitive actions as used by industrial robots in automotive assembly lines and other manufacturing automation. The expanded definition as used here includes autonomous actions that go beyond fixed routines and make use of machine intelligence to interpret tasks and environmental constraints in order to determine action. Both forms of robotics will have uses in the proposed YM repository operations.
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> *Telerobotics* is the merging of teleoperation and robotics—direct human control of manipulation (or mobility) plus automation (robotics) to improve some aspect of the remote task. The general objectives are to decrease task completion time, to improve the quality of the task completed, and to reduce operator fatigue and so improve operator efficiency. While all telerobotics is some combination of teleoperation (human-directed) and robotic (automated) execution of tasks, the accent on telerobotic capability can be placed on either teleoperation (Tr) or robotics (tR). Tr requires high-fidelity (high-quality) teleoperation; tR requires some teleoperation capability to provide automated/robotics systems with task error recovery but emphasizes robotic positioning. The relevance of this to YM is discussed in the various topics.

Important research issues in sensor-based robotics or telerobotics include the following:

1. Which portions of a task sequence should be teleoperated, what portions of a task should be automated to provide the greatest improvements, and how should these components be implemented?
2. How is the automated part of the task programmed, scripted, etc.?
3. How is the switch between the two modes—teleoperation and robotic—completed seamlessly with minimal confusion to the operator?
4. How is the automated portion of the task integrated with the teleoperation portion for optimum efficiency (time and cost)?

Significant research is ongoing in this area. Many DOE laboratories and U.S. universities and a few U.S. companies have current work in progress in this area. Other countries with nuclear programs—primarily France, England, Germany, and Japan—have also funded similar efforts. Many of these countries have commercial companies tightly coupled with government organizations involved in this work. Due to the variability of tasks and the primary applicability to the above-ground material handling facility and off-normal event incident recovery, the proposed YM operations will always require efficient teleoperation capability and therefore should invest primarily in the Tr category of telerobotics. Investment in tR type of telerobotics would be useful in the context of recovery from off-normal events in the CC.

The expected return on investment if these efforts are successful is deemed to be high. While any R&D effort has risks, the risk of failure appeared to be limited, since there would most likely be some gain in capability regardless. As delineated here, this task is primarily oriented towards manipulation; however, it is also applicable to mobility.

Application areas include the above-ground material handling facility as well as any below-ground remote operations, including performance confirmation and off-normal incident recovery.

Vision-Based Robotics (Visually Guided Manipulation)

Visually guided manipulation can be viewed in two ways, both of which are fundamentally useful for accomplishing proposed YM tasks. First, vision-guided manipulation may be considered a subset of sensor-based or -guided manipulation in terms of planning and executing tasks for sensor-based robotics and can therefore be grouped with the preceding task (i.e., vision-based sensor-based tasks should not be excluded from the previous topic and may be the dominant proposal). Second, there is a more generic need for visual servoing capability to correct positioning errors inherent in large-flexible (compliant) remote systems working with target objects that have not been registered to the robot system. The term visual servoing generally means vision-based tracking of objects for the purpose of accurately positioning a manipulator to mate with the object. As used here, it refers to a means of correction between where the robot "thinks" it or its target object is as opposed to where the object actually is in 3D space. This is a general problem that must be addressed to permit real-world 3D modeling and task execution for a wide variety of telerobotics tasks. Over the last 10 years, many image-processing professionals have begun to look at visual servoing. However, most work to date has focused primarily on two dimensions (flat), highly constrained working environments (an oversimplified, high-contrast background-to-target object ratio), or systems that will not run in real time and are therefore unsuitable to drive manipulator positioning during task execution. There appears to be a consensus in the research community that focused research could produce usable results relevant to the proposed YM operations.

Important research issues include the following:

1. Target object identification and tracking in cluttered, real-world backgrounds and the capability for an operator to seamlessly identify an object to interact with, while planning and executing a telerobotic task.

2. Image-processing techniques that work robustly in real time to track complex objects in 3D, real-world environments. This is a major limitation to the real-world use of visual servoing at this time.

3. Techniques and algorithms to minimize the impact of the camera resolution vs. field-of-view tradeoffs. This is a major limitation to the real-world use of visual servoing at this time.

The probability of return on investment is high if this effort is successful, while the risk associated with failure is medium to low due to the R&D nature of the effort. As noted earlier, the concerns with the payback are related to issues that must be overcome to make this technology viable for proposed YM repository use. Because a manipulator would need to be mounted on a mobile platform to have value in either the above-ground or below-ground facility, this task is relevant to manipulation, mobility platforms, or a combination of the two.

Application areas include tasks in the above-ground material handling facility as well as any below-ground remote operations, including performance confirmation and off-normal event recovery.

Non-Contact Precision Drift Wall Inspection Sensor System

The purpose of a non-contact precision drift wall inspection sensor system is to supply scanning, imaging, and data archiving of the proposed YM drifts (tunnels), preferably but not necessarily in real time, so that an initial baseline can be established as to the initial state of the drift, and so that periodic reinspections and baseline comparisons can be made to assess the structural integrity of the drifts and tunnels over time. This is a high-priority task at the core of verifying the integrity of the proposed YM underground facility. Progress has been made in recent years both in the imaging of large objects and in the image processing necessary to categorize, store, retrieve, and analyze data. An existing technology base is established; however, a technology has not specifically been targeted and optimized for the task of drift characterization, documentation, and data analysis.

Research or development issues include

1. optimization of scanning for drift conditions—e.g., resolution, lighting; and

2. database optimization for visualization and records management purposes.

A directed R&D project along these lines would have a high probability of producing technology that is directly relevant to YM. The probability of a favorable return on investment is high; the probability of failure is low, since there is some existing technology base, and a useable technology is probable though it may not meet the highest goals for performance. This is probably more of a development activity than a research activity. The specific application area is that of below-ground drift inspections.

In Situ Waste Package Weld Inspection Sensor System

Welding and weld mitigation completion times in the CC are driven almost exclusively by the welding or mitigation technology. The CC itself is configured as a structured industrial robotics work cell. While there are issues, robotics is not a primary driver in efficiency in the CC task. However, inspection of the welds is a sensor-systems issue relevant to this study. This task requires a sensor system for time-optimized inspection of the remote welds made on the WP in the CC. Issues include 3D visual data collection for inspection and archiving for documentation purposes, the use of multiple sensors to verify weld integrity, advanced sensor fusion techniques (multiple sensors merged into one output to obtain more data and/or increase the quality of data), and operator interface technology to present the inspection results in a meaningful format to a human operator overseeing the inspection process. High-quality weld inspection is an absolute requirement; however, weld inspection must also be completed in minimum time to optimize plant throughput.

Research and development issues include

1. identification of sensor technologies to fit the specific task—e.g. resolution, execution time;
2. sensor fusion of the various signals for complete information about weld quality; and
3. presentation and record keeping of the data for verification.

No complete package capable of doing these tasks in a timely manner is known to have been developed; however, significant work has been done on weld inspection technologies, sensor fusion, visualization, etc., so it should be possible to develop an integrated system, given OCRWM/OST&I funding. The probability of some degree of success is high; the probability of a good return on investment is also high, since any time-reduction in weld inspection translates to increased throughput. This topic has a specific focused application relevant only to the WPs in the CCs.

Advanced Human-Machine Interfaces

Along with sensor-based robotics and telerobotics and dexterous manipulation, advances in remote system human-machine interfaces are necessary to improve the efficiency of operation and to reduce fatigue such that smaller work crews can complete a given task. The sense of "presence" that an operator "feels" while conducting a task via teleoperation directly impacts task performance. Under some operating modes, the more the operator "feels" hands-on doing the task, the better the task execution and efficiency. Overall, this is referred to as the "transparency" of the operator interface with all sensing systems—remote viewing, audio, and a physical sense of force and touch feedback in the hand controllers of the manipulator. Another aspect of the operator interface includes how the operator interacts with the system controller for task function selection and for switching between manual and automated/robotic modes. The difficulty in defining this activity is that it is difficult to separate functionally from the associated tasks of sensor-based robotics/telerobotics, visual servoing, or dexterous manipulation. However, there may be some proposals that could be applied across the board to the various technology areas that could be considered under this topic.

Research and development issues include

1. remote vision systems providing depth perception and optimization of "presence" while still allowing multiple views and integration of graphical user interfaces for mode selection and setup of telerobotic or robotic tasks;
2. seamless transfer between robotic and teleoperation modes of operation;
3. graceful recovery from automation faults; and
4. novel task scripting interfaces to minimize task setup times.

The probability for success in this application area is moderately high; the difficulty lies in producing effective 3D visualization and haptic (sense of touch) interfaces that could be used for hours at a time without fatigue. The potential payback is high but would be directly linked to the associated sensor-based robotic/telerobotic or dexterous manipulation capability. The area of application for this capability would be in the above-ground material handling facility and all remote operations below-ground, including performance confirmation activity and all incident recovery operations.

Conversion of Gamma and Neutron Radiation to Electricity for On-board Robot Power

The purpose of the radiation-to-electricity conversion technology task is to find a way to make use of the ambient gamma radiation field to provide power. The technology would be similar in technique to the way in which a solar cell uses solar energy to generate electricity. While the high-radiation access robotic and remote systems for the proposed YM repository can be primarily rail-driven and powered, multiple needs still exist for mobile robot systems to enter where limited-access areas or areas where normal access has been constrained for various reasons. A stand-alone power source is needed. In addition, many sensor applications would benefit from an independent power source. Most if not all battery and generator concepts are unacceptable for these applications and would have limited operation times. A rad cell would make use of ambient radiation to provide long-term operation.

Research issues include

1. definition of the physics and a study of the feasibility of the energy conversion process along with calculations on the available energy fields generated; and
2. experimental verification of physical prototypes.

The probability of return on research investment (real value) if the effort is successful is extremely high; however, the risk of failure due to the R&D nature of this problem is significantly high as well. Since the value is so high, a directed study of feasibility should be funded at the very least.

The almost exclusive application of this technology to the proposed YM repository would be for robots and remote systems that need to enter the high radiation fields present in loaded drifts of the subsurface facility to take measurements (performance confirmation or otherwise) or to recover from incidents. The one far-reaching possibility if this technology development were to be successful is that it could potentially reclassify material from waste to an energy resource.

Approach for Radiation-Hardened High-Temperature (200 rad/hour, 200°C) Electronics

Typically, radiation hardening of electronics involves an iterative process of testing to identify weak components, followed by the selection of more radiation-tolerant replacement components, followed by further testing. This is a tedious and expensive process that produces results specific to the particular model of equipment “hardened.” The value of this approach for rad hardening is diminished by the trend to short life cycles for electronics-based equipment (personal computers now have at most an 18-month obsolescence cycle) and the long lifespan for the proposed YM facilities and equipment. This technology task addresses development of an electronics family that is inherently radiation- and temperature-hardened and could be used in a wide variety of controls and sensing modules throughout YM to improve radiation tolerance and increase operational life, thereby decreasing maintenance costs and increasing operating time in high-radiation fields.

Some radiation-tolerant electronics components and subsystems have been developed for space applications; however, their dose rate tolerance is insufficient for proposed YM applications. There are also some nuclear-based applications such as radiation-hardened cameras; however, these systems cannot sustain the long lifetimes that the proposed YM applications require, and the technologies generally lag significantly behind current commercial technologies. The number of suppliers of radiation-hardened components and technologies has drastically decreased in the last 15 years as the government has phased out programs that require radiation-tolerant electronics. Commercial market need and interest are not sufficient to warrant attention to this area outside of government funding.

While this research area could be used to conduct traditional hardening of various system components planned for proposed YM applications, the real research need is for an overall strategy, philosophy, and system to generate radiation-hardened high-temperature electronics across the board for use in the proposed YM systems—robotics, remote systems, and sensor systems. This implies the use of technologies to make electronics circuits that are not commonly in use at this time. One example of a potential technology for both radiation-hardened and high-temperature electronics is the use of silicon carbide–based integrated circuit material. However, this task should not be limited to this technology; it is only used as an example to indicate that potential solutions exist.

Research issues include

1. development of electronics families that are inherently radiation- and high temperature–tolerant; and

2. development and definition of technology guidelines for use of the novel technology families, since it is likely that they will have radically different operational voltage ranges, levels of integration, and the like.

There are relatively few participants in the general field of radiation-tolerant high-temperature electronics at this time; a few military/space-oriented suppliers, government laboratories, and universities have the potential to contribute.

The return on investment for development of this technology, if successful, would be high; however, the risk of failure is also significant, since this would be a serious research effort with many unknowns at its start. Given that the value of such research to the proposed YM repository is potentially large and that it is highly unlikely anyone else would produce this capability for any other market, this is a topic that OCRWM/OST&I should seriously consider funding.

The area of application is generic to the entire proposed YM facility wherever remote systems must be used, but the areas most likely to benefit are underground operations and performance confirmation activities where the radiation levels are high and exposure time is long. Above-ground tasks where exposure time is not long but radiation levels are high would also benefit.

Dexterous Manipulation

Teleoperation based on high-quality servomanipulators currently requires 5 to 15 times longer for task completion than “hands-on” operations. In addition, there is a fatigue factor that limits the duration of work sessions, requiring more staff that otherwise might be necessary. The desired goal for a dexterous manipulation technology is improved teleoperation that allows the operator to feel that he or she is working in a hands-on mode, even though the operator is working remotely. For this to happen, the task completion ratio must be as close as possible to 1:1. This requires improved force reflection, sensitivity, the use of tactile sensors on hands and fingers instead of parallel jaw grippers, and improved remote viewing and operator interfaces so that the operator can see operations as if he or she were “present” but still be able to interact with auxiliary views and the supplemental data presentation generally required to operate any remotely controlled system. Using the currently accepted technology terminology, the quality of operation or degree of “transparency” of operation must be improved by approximately an order of magnitude.

The National Aeronautics and Space Administration (NASA) and the Defense Advanced Research Projects Agency have been jointly funding a project called Robonaut at NASA’s Johnson Space Center with major support from Lockheed-Martin. Robonaut is an “astronaut replacement” type of anthropomorphic (humanlike) remote system. The robot has two arms, each with five-fingered hands, mounted to a human-appearing and human-scale torso and a head with stereo viewing cameras. The system is not particularly robust for DOE-type applications (being designed to operate in zero gravity), has low bandwidth (slow motion), does not have the same temperature and radiation constraints as required by the proposed YM repository (though space does constitute a hazardous environment), and does not have a suitable ground-based mobility system for a DOE hazardous environment. However, many of the research issues are the same. Robonaut could be used as a model and a baseline concept with no affiliation to NASA, or a teaming between NASA and DOE, a university, or commercial entity could be encouraged.

Research issues include

1. kinematics studies for optimum configuration of master controllers and manipulators, including hand-type end-effectors;
2. master controller concepts and designs;
3. actuator design schemes;
4. control system algorithms for optimized transparency;
5. human factors issues with respect to optimizing total system (operator + remote system) performance;
6. force and tactile feedback;
7. mobility platforms for above ground and below ground facilities; and
8. operator interfaces to optimize interaction and to enhance the “transparency” of operation to the operator.

The return on investment is exceptionally high for any remote systems tasks, whether routine or off-normal event incident recovery. The probability of 100% success is difficult to determine, as this is a research topic and not on the development end of the scale. However, there would almost certainly be some degree of benefit returned for the investment spent in terms of improved efficiencies and decreased task times.

The areas of application for this topic would include anywhere that remote systems are necessary in the above- or below-ground facilities; however; the benefit would be most relevant in dealing with off-normal events, incident recovery, or routine operations where the equipment interacted with had not been designed for remote interaction.

Remote Operations and Maintenance Studies

Remote operations and maintenance studies do not constitute a technology area per se but do represent a definite area for investment to improve the cost of operations and the throughput efficiency for all of the repository facilities where remote handling is required.

This task will analyze the above-and below-ground remote-handling facilities and capabilities in the context of a "design for remote" optimization approach to produce equipment, process, and facility modifications that will optimize throughput and minimize costs of operation. Efficient remote operation requires an approach of "design for remote" that includes not only the remote systems and the tooling that they use but also the tasks, processes, and facility integrated with the remote systems. Along with this design for remote orientation, a study of off-normal events and their possible solution must be included. This design approach works with established guidelines and technologies, combined with mockups for testing, verification, and training, to improve the efficiency of remote operations. Done correctly, these design studies can lead to significant improvements in operating efficiency. While the nuclear power industry may have some degree of expertise in this area, typically only the DOE laboratories have addressed this to any significant degree. This is not the venue of commercial companies or universities.

Proposed work for this topic will include complete process flow analyses of tasks, equipment, facility, and work force in the context of design for remote optimization.

The probability of payback on this activity is extremely high, since it focuses on optimization of currently available state-of-the-art equipment. Technology development is not the focus; this is a process optimization and verification task. The risk of failure is low; there would almost certainly be a major degree of value to be gained from this study. The degree of success would be the only issue. The only caveat to this task is that design for remote is generally something that must be instituted early in the design stages of a facility; it is generally difficult to make gains by retrofitting an existing facility. The areas of application for this topic include the entire facility—above and below ground—wherever remote operations are required.

CONCLUSION

The objective of this evaluation was to generate a list of recommended robotics, remote handling, and sensor technologies to improve the operating efficiencies and cost factors of the proposed YM repository, and present those technologies as a multiyear R&D program for OCRWM/OST&I to use as a road map for future consideration. This paper presented only the high-priority items—i.e., those with the greatest potential for improving the efficiency of operations and reducing cost.

The study found that there is a potential for major improvements in efficiency and operating costs if the recommendations for the proposed OST&I program are implemented. The recommended technologies and projects offer the majority of improvements; thus, a fairly small and concise R&D program could be initiated with potential for major benefits. Other topics for future consideration have been identified and listed as appropriate. A summary of these recommendations is presented here, emphasizing those items that should have the highest payback for the proposed YM repository.

Robotics and remote handling. *Telerobotics*, with an emphasis on sensor-based control and *dexterous manipulation* are the two key technologies in this area that will benefit YM. Many dexterous plant processes require extensive remote operation; however, remote operation requires 5 to 15 times as long as hands-on operation to complete a task. The focus of these two tasks is to bring that time-related inefficiency closer to a one-to-one ratio of task completion time. Sensor-based telerobotics improves task efficiency by supplementing human control with task automation; dexterous manipulation improves task efficiency by improving the operator's sense of hands-on "presence" with the task.

Operations, maintenance, and security. *Remote operations and maintenance studies* focus on remote processes in the context of optimization by a "design-for-remote" philosophy. It is a process optimization area based on the use of currently available state-of-the-art technology in conjunction with best practices design of the remote facility, task hardware, manipulation systems, and tooling. Operator issues are also included. While not a technology development task, this topic has a high certainty of delivering significant cost savings over the life of the facility.

Sensor systems. A *weld package inspection system* and a *drift wall inspection system* are the suggested technologies in this area. Much of the plant throughput is dependent on minimizing time spent in the CC during welding, weld mitigation, and weld inspection. Welding and mitigation are time-driven processes that cannot be affected without major changes in the technology used (the topic of another OST&I program); however, weld inspection also requires significant time. The proposed sensor system topic should significantly reduce this inspection time while improving data archiving for the WPs. While the drift wall inspection system should produce noticeable time, and therefore cost, savings, the primary benefit is in the quality of data collected and archived on drift integrity.

Support systems. Topics in this area include the *high-temperature radiation-hardened electronics family* and a r*ad-based power cell/generator*. The primary effects of these topics are not so much to save operation time and cost directly as they are to save on maintenance costs and activities and/or to extend the possible operating time in the hazardous environments to extend capability. Cost and labor saving and extended operating time will have an indirect effect on improved operations and therefore cost to complete given tasks. The high-temperature, radiation-hardened electronics topic works to push the envelope of radiation and temperature tolerance by two orders of magnitude over the current state of the art. The task also moves away from the traditional iterative augment-and-test approach in favor of the development of inherently radiation-hardened technology. The radiation-based power cell is a fairly radical divergence from current technology with an attempt to produce an equivalent to solar cells with gamma radiation. This is the highest-risk topic on this list; however, the potential for payback is extreme, and there is a strong desire to extend the operating range of untethered remote systems.

Project funding should be awarded for three years, with the potential for renewal for another two years pending consistently good reviews of development activities. Most of these topics will require three to five years of consistent, uninterrupted effort in order to provide value to proposed YM project. Technology development projects, though awarded for the three-year initial or a two-year final increment, should undergo annual peer review of technical progress and project management practices in order to receive validation for continued funding.

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