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Modular Manipulator for Robotics Applications

Industry Programs and
Deactivation and Decommissioning Focus Area

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INNOVATIVE TECHNOLOGY
Summary Report

Modular Manipulator for Robotics Applications

Tech ID 2199

Industry Programs and
Deactivation and Decommissioning Focus Area

Demonstrated at
ARM Automation, Inc.
Austin, Texas

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under "Publications."

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SECTION 1
SUMMARY

Technology Summary

Problem

Across the Department of Energy (DOE) complex, gloveboxes are widely used to handle radioactive and hazardous materials. Most glovebox operations are performed manually through lead-lined gloves. Automation of these operations using robotic technology reduces human exposure to radiation and increases productivity. The use of glovebox robotic automation technology is critical to the DOE's efforts to accelerate cleanup (US DOE, "Accelerating Paths to Closure" 1998) and complies with its mandated "As Low as Reasonably Achievable" (ALARA) principles. Incorporating robotic automation into a glovebox environment offers a unique set of challenges. Maintenance and repair are significant issues when considering the glovebox environment. Routine maintenance and repair can become very difficult or impossible when these tasks must be accomplished inside the glovebox through bulky gloves. A broken piece of equipment that is not repairable, must be bagged-out and removed from the glovebox through a glove port. Robotic automation equipment must also be compatible with existing gloveboxes that may not be easily modified to accommodate new equipment. Developing robotic systems that are compatible with the harsh radiological and chemical properties of the materials handled in a glovebox, such as plutonium, is also challenging.

How It Works

ARM Automation Inc. (ARM) has developed a system of modular robotic components, designed to address many of the challenges discussed above. This manipulator system is capable of custom configurations and is applicable to common glovebox tasks such as materials repackaging. The system is modular and has quick connects between components to simplify installations into "hot" boxes and any potential modifications or repair therein. The modular manipulator system developed for glovebox applications is pictured in Figure 1.

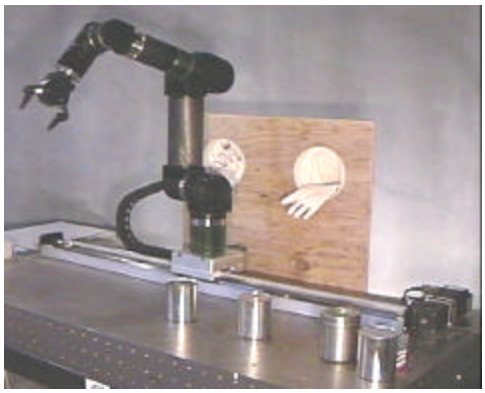

Figure 1. Modular manipulator configured for plutonium repackaging.

The modular approach to automation, which utilizes a small set of versatile actuator modules, can be used to construct a broad range of robotic systems and automation cells suited to DOE applications. By providing a pre-engineered, pre-integrated motion system to different robotics users within the DOE, new automation systems can be created quickly without extensive expertise in motion control or the expense of building custom equipment from scratch.

ARM's line of modular components is built upon a core technology called Distributed Intelligent Servo Control or DISC™. Each DISC™ device is a miniature control and digital communications node, which may be linked with other DISC™ devices to create a distributed control network of motion devices and sensors. The versatility, ease of use, and small size of these controllers allows them to be tightly integrated throughout the mechanical structure, thereby reducing system size, cost, design, wiring, maintenance, and overall complexity. The reduction in wiring realized by the distributed approach is mandatory to make the mechanical modularity feasible. Through the commonality and versatility of this controller, an entire family of automation devices can be created which share a common distributed control architecture, communications protocol, programming scheme, and simplified electrical interface. At present, all DISC™ devices utilize an industry standard communications protocol called SERCOS (Serial Real Time Communications System). This open protocol provides deterministic, high-speed communications, and is supported by many vendors of motion control components. This architecture allows for a single communications link between all devices under system control. Support for other protocols may be integrated based upon customer interest.

Potential Markets

There are many needs within the DOE Complex requiring glovebox automation, but immediate needs exist at the following sites: Savannah River Site (SRS), Los Alamos National Laboratory (LANL), Argonne National Laboratory (ANL), Sandia National Laboratory (SNL), Hanford Site, and Rocky Flats Environmental Technology Site (RFETS) (US DOE, Nuclear Materials Focus Area 1999, Lyman 1998, Dyches, et. al. 1999, and McKee 1998).

Advantages Over Baseline Technology

In most cases the baseline technology for glovebox operations is manual handling. The primary advantage of the Modular Manipulator over manual handling is reduced worker exposure to radiation. In terms of robotic technology, the baseline technology used by LANL in its Advanced Recovery and Integrated Extraction System (ARIES) for separating plutonium from nuclear weapons components is the Fanuc LR-Mate 100i™ commercial robot. ARM's modular robotic technology has the following advantages over the LR-Mate 100i™:

- Increased net payload to weight ratio, and increased wrist payload;
- Reduced the umbilical cord from 100 wires to 12 wires;
- Modular components are reconfigurable, allowing customization of manipulator system; and
- Modular components facilitate ease of installation, maintenance, and repair inside glovebox.

Demonstration Summary

The system was successfully demonstrated at ARM's laboratory facilities through two separate activities. The first task demonstrated the usefulness of the quick connects for passing the modules through the glove port and assembling the manipulator. The second task demonstrated the ability of the system to perform a typical procedure involved with the processing of pure Plutonium into a mixed oxide (MOX) fuel: inserting a convenience can filled with plutonium into a hermetically sealed stainless steel primary can.

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Other

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under "Publications." The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The Tech ID Modular Manipulator for Robotics Applications is 2199.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

ARM automation has developed a modular actuator and related components that are the framework for reconfigurable, modular, robotic manipulators. These modular robotic systems are well suited to automation of glovebox operations. For this project, the modular actuators were configured into two robotic systems for Automated Plutonium Processing (APP) operations. These modular manipulators are just two examples of the systems that can be built from the modular actuators and components developed. The systems built for this project display all the features and performance traits that are characteristic of the modular robotic architecture.

The manipulators built for this project were configured for use in applications similar to those of LANL's Advanced Recovery and Integrated Extraction System (ARIES). The ARIES demonstration system separates plutonium from other weapons components as part of the nuclear weapons dismantling process. The ARIES system consists of a series of glovebox modules used to extract plutonium from the nuclear trigger, or "pit", of a nuclear weapon in preparation for storage, disposal, or alternative-use. In this process the extracted plutonium is converted into an unclassified form, packaged, and assayed. One of the glovebox modules is a canning and decontamination process. In this module the processed plutonium MOX product contained in a convenience can is placed in a stainless-steel primary can. This activity is the basis for the systems demonstration described in Section 3.

Modular manipulator systems consist of the following major components: actuator modules, links, yokes, quick connects, umbilical cord, end-effector, and system controller with an integrated power supply. Each of these components will be described below.

Actuator Module

The actuator module is the heart of the modular manipulator system and the system's most innovative aspect. In the field of automation and robotics, an actuator is a common element used to generate motion for precise positioning of loads. Within the context of this paper the term "actuator module" refers to a component of a robotic system that consists of a tightly integrated package containing an electric motor, gear train, output support bearings, position sensors, brake, servo-amplifier, and communications control. One example of an actuator would be an individual joint within an industrial robotic manipulator.

Each actuator module in this family of modular "building blocks" is based upon a core technology called the DISC™. Each DISC™ device is a miniature control and communications node that can be linked with other DISC™ devices to create a distributed control network of motion devices and sensors. DISC™ devices communicate using an industrial communications protocol called SERCOS, which is specifically designed for high-speed communications between motion control devices. The distributed control, combined with this digital communications protocol, provides noise immunity, real-time communications, and most importantly reduces the large number of control wires associated with traditional motion control systems to a single twisted pair or fiber optic ring. By providing a uniform interface to each element of an automation cell at the hardware, software, and protocol levels; complex automation systems can be designed, built and maintained with less time and expertise than required by conventional approaches.

In order to construct a variety of robotic manipulators for different applications, two sizes of actuator modules were designed for this project: the ARM20 and ARM32 actuators. Each actuator module incorporates a DISC™ amplifier along with a high performance brushless DC motor, position/velocity sensors, gearing, structural bearings, fail-safe brake, and other components to form a pre-engineered package (See Figure 2). Each actuator module utilizes a standardized electro/mechanical interface, which allows a simultaneous connection of electrical power and signal, pneumatic supply, and a precise mechanical connection. The specifications for the ARM 20 and ARM 32 actuators are provided in Table 1.

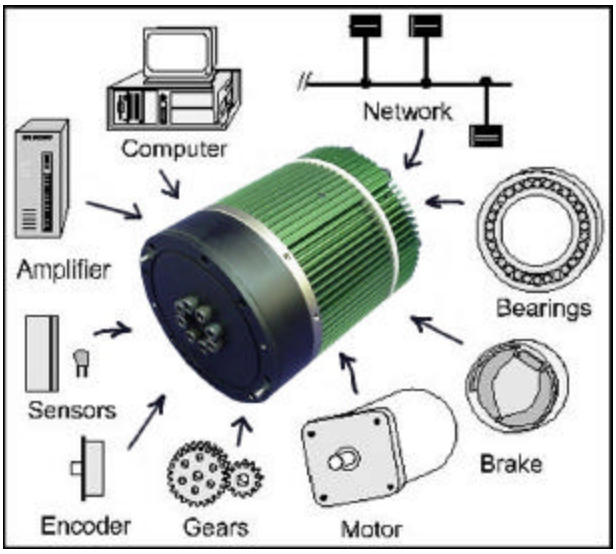

Figure 2. ARM actuator module

Table 1: Actuator module specifications.

Model	**ARM20**	**ARM32**
Performance*:*		
• Range of Motion	± 270°	± 270°
• Output Peak Speed	36 RPM with 80:1 Gear train	23.4 RPM with 100:1 Gear train
• Output Peak Torque	74 N·m	298 N·m
• Output Continuous Torque	47 N·m	130 N·m
• Bearing Load Capacity (axial/radial))	20,000 N/1,600N	23,800N/10,700 N
• Bearing Overturning Load	210 N·m	700 N·m
• Voltage Input Range	60 - 320 Volts	60 – 320 Volts
• Rated Current (Cont/Pk)	1 / 2.5 Amps	3.0 / 4.5 Amps
Physical:		
• Length	115 mm	159 mm
• Diameter	97 mm	129 mm
• Mass	2.42 kg	6.1 kg

Yokes, Links, Quick Connects, Umbilical, and End Effector

Robotic arms can be assembled in a variety of kinematic (geometric) configurations by selection of appropriate actuators, links, and yokes. Each link module is simply a tubular or linear extension of an actuator module, while yoke adapters convert modules into pitch joints (see Figure 3). Pitch actuators can be thought of as the “bending” point in a serial arm. Variations on yoke adapters allow the creation of pitch joints, which are full-offset, in-line, double-yoke, or almost any custom offset. While link modules typically take the form of cylinders extending the length of roll actuators, they may also be built as a “parallel-links” for maximum stiffness between two consecutive pitch modules.

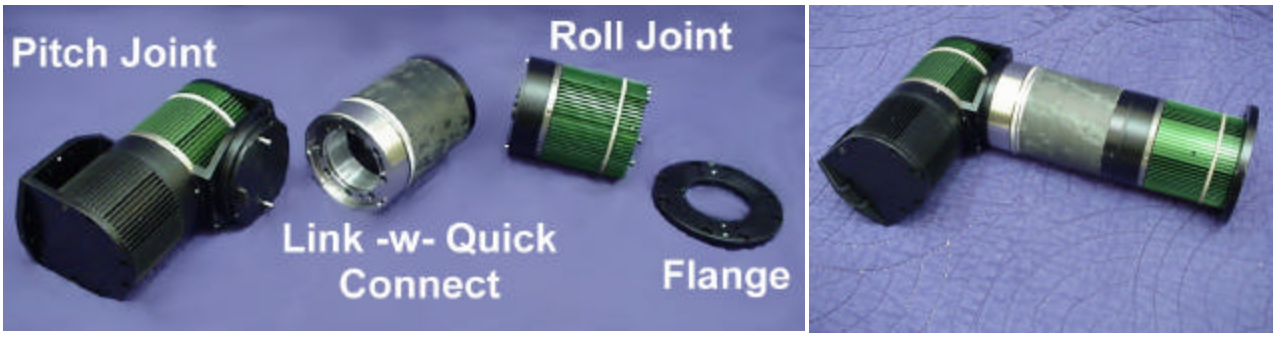

Figure 3: Several ARM20 elements of the modular manipulator system unassembled (left) and assembled (right).

In order to allow safe and efficient field serviceability for EM applications, a novel quick-connect mechanism was created so actuators can easily be joined with, or separated from adjacent modules (see Figure 4). Within a single quick-connect interface, electrical, mechanical, and pneumatic connections are made simultaneously. These stiff interfaces are capable of sustaining the high internal forces and the only tool required for joining or breaking the connection is a simple spanner wrench. Quick-connections are extremely simple to operate and minimize pinch points that present a hazard to gloves and other worker protective barriers.

The two halves of each quick connect flange are joined by aligning the electrical connectors and dowel pins of each flange, mating the halves together, and rotating by hand an interlocking collar through approximately 45°. Once the interlocking collar is hand tightened in position, the joint is secure and the operator may release the module being attached. To fully secure the quick connect mechanism to specifications, the operator may apply a simple spanner wrench to the knurled collar and rotate until sufficiently tight.

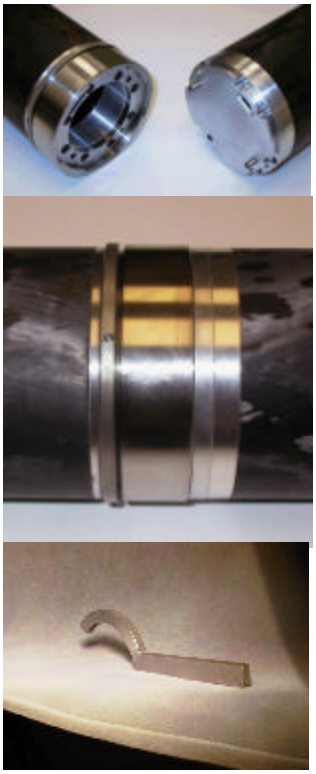

Figure 4: ARM quick -connect mechanism

The umbilical cord for the manipulator is comprised of a 7 wire cable, a two pair, shielded twisted pair cable, and a pneumatic line. The 7 wire stranded cable is an Olflex cable for the following signals: Earth Ground, Main Bus Power (2 wires), Control Power (+24 V) (2 wires), and end-effector power (2 wires). The twisted pair cable is for the SERCOS communications system.

The end-effector utilized in testing was an off-the-shelf TRI gripper, model DP100/30. This is a simple open/close gripper that operates from a 24 V supply. It was chosen because of its availability rather than as an ideal solution.

Integrated Power Supply and System Controller

The manipulators are controlled using the integrated power supply and system controller. The power supply contains the utility interface, the main power conditioning circuitry, the control (24 V_{DC}) supply, the system controller power supply, a Power Supply and System Controller Interface (PSSCI) board, relay control logic, and the system controller. The supply can be configured to interface to either single phase 120 or three-phase 208 V_{AC}.

The system controller contains an industrial Personal Computer (PC) combined with a power supply in a single enclosure (typically, 19” x 17” x 7”). The PC is an inherently flexible platform, which includes a SERCOS compatible motion control board for coordinating axes and issuing real-time commands onto the network. By using PC based hardware, virtually any open-architecture system control software can be used to run this system. For the systems being designed during this project, Cimetrix system controller software has been selected to provide the ability to program, run simulations, and provide a graphical user interface.

The system controller is a single board computer consisting of an Ethernet controller, an Integrated Drive Electronics (IDE) controller, a PC-104 expansion bus, several digital input/output (I/O) and analog input lines, and a Pentium® Class processor with 64MB of memory. The system contains a 4 Gigabyte hard drive. A Motion Engineering, Inc. (MEI) SERCOS motion control card is resident on the PC-104 bus. This card is used to control the trajectories on the individual axes. The system controller's operating system is Microsoft® Windows® NT 4.0.

The system controller coordinates the motion of the joints. The software control architecture chosen for this project is a open-architecture system developed by Cimetrix. This controller uses a client-server format with the server running in the power supply and the client running either on the power supply or externally and communicating to the server using a Transition Control Protocol/Internet (TCP/IP) Protocol. The client generates the manipulator's joint set points and passes them to the server. The server then generates the desired motion profile and passes the commands on to a motion card interface. The server monitors external signals through the I/O signal interface. The CODE (Cimetrix Open Development Environment) interface is a set of library function calls that creates the interface between the user's application environment and the server. The user develops an application in C, Visual C++, Visual Basic, or Delphi using library CODE function calls supplied by Cimetrix. These function calls then pass information to the server. The server is a multi-threaded program operating on an NT 4.0 platform that performs the motion control, error monitoring, and I/O control. The server then passes motion commands to the motion I/O card interface.

System Operation

Two different manipulator systems were developed during this project: (1) a more complex system, which offers flexibility in meeting the needs of a wide range of glovebox tasks and (2) a less complicated, system which meets the specific requirements of the ARIES or the Plutonium Isolation Project (PIP) automation cells. The second system is simply constructed by removing modular components from the first, and can be configured within a brief amount of time. The operational parameters of the two manipulators developed for this project are provided in Table 2. For comparison the operational parameters of the Fanuc LR Mate 100i™ are also provided. The Fanuc LR-Mate 100i™ is discussed in greater detail in Section 4.

Table 2: Modular manipulator and Fanuc LR-Mate 100i™ specifications.

Item	Manipulator #1	Manipulator #2	LR-Mate 100i™
Degrees of freedom (DOF)	4	4	5
Wrist Payload	3 kg	9.5 kg	3 kg
Mass with 1.2 m Track (26.3 kg)	40.9 kg	51.9 kg	58.3 kg
Mass with Base Roll	18.3 kg	34.58 kg	32 kg
Repeatability	+/- 0.08 mm	+/- 0.08 mm	+/- 0.04 mm
Reach from base pitch to Wrist Plate	640 mm	960 mm	620 mm

The actuators incorporate an absolute position sensor that is factory calibrated. Upon power up, an actuator reads its output position and then moves or 'homes' in the direction of the nearest index pulse on the input. The total homing procedure requires the output to move less than 3.6 degrees regardless of the initial position of the input. Thus, the actuators can be assembled, disassembled, reconfigured and reassembled without recalibration. Unlike conventional methods that require the actuator to home to their extreme limits, these actuators only have to move a small amount allowing them to be homed in confined spaces.

The application environment is an off-the-shelf open architecture system developed by Cimetrix. Inc. The software environment provides a suite of open architecture robot modeling and motion control tools designed to control any multi-axis robotic applications. This environment consists of three components: CIMControl, CIMulation, and CIMTools. CIMTools allows the user to model a robot and its application. The model developed in CIMTools generates the D-H parameters for use in either CIMulation or CIMControl. CIMTools also provides a software teach pendant interface for controlling a manipulator and teaching points for automation. CIMulation is a 3-D solid modeling program that is used to simulate robotic models developed in CIMTools. This is useful for verifying the accuracy of the model parameters and application environment

for specific operations developed in CIMTools before they are run on actual hardware. Finally, CIMControl is used to develop applications and run them on real hardware. CIMControl runs on top of the standard operating systems of Unix and Windows NT. Applications can be developed in standard languages, using standard development environments such as Visual Basic, Visual C++, or Borland Delphi. CIMControl provides all of the necessary functionality to control the modular manipulator for any given application including trajectory generation and error checking.

CIMETRIX provides the necessary functionality to make the modular manipulator operate similar to any off the shelf manipulator's system controller. Additionally, CIMETRIX allows the user to change the kinematics using CIMTools each time the system is assembled into a new configuration. The system model can then be verified in CIMulation and controlled using CIMControl.

SECTION 3
PERFORMANCE

Demonstration Plan

The overall purpose of this project was to show that modular robotics is an improved technology to address the needs of DOE's EM program. A more specific objective of the project was to demonstrate the capabilities and benefits of modular manipulators for the automation of glovebox operations. To support this objective, the technology demonstration included two tasks. The first task was to demonstrate the usefulness of the modular approach and the quick connects for assembling the manipulator inside the glovebox. The second task was to demonstrate the manipulators ability to perform an actual glovebox activity. The glovebox activity selected for this demonstration is a task associated with the separation of plutonium from other weapons components.

As discussed in Section 2, the manipulators built for this project were configured for use in systems similar to the Advanced Recovery and Integrated Extraction System (ARIES), being demonstrated at LANL. The ARIES demonstration system separates plutonium from other weapons components as part of the nuclear weapons dismantling process. One of the glovebox modules is a canning and decontamination process. In this module, the processed plutonium metal or oxide product contained in a convenience can is placed in a stainless-steel primary can. This particular task was chosen to demonstrate the performance of the modular manipulator system due to its level of difficulty. This operation is difficult because precise positioning is required to meet close clearances. The demonstration activities were performed at ARM Automation's facilities and all demonstration activities were video taped.

Assembly Of Manipulator Using Quick Connects

To demonstrate the benefits of the quick-connect system, the modular manipulator system was assembled through a simulated glovebox. For the demonstration, a joint, link and half of a quick connect were assembled external to the glovebox and then passed into the glovebox through a glove port. The linear track along which the manipulator travels can also be passed through a glove port. The pieces of the manipulator were assembled in the glovebox by the following procedure:

- Locate retaining ring in open position.
- Pick up adjoining module assembly and insert it into the quick connect by aligning dowel pins.
- Turn retaining ring into closed position.
- Use spanner wrench to secure link in place by turning the preload ring.
- Repeat with next joint

Assembly of A Convenience Can Inside A Primary Can

The capabilities of the modular manipulator, developed under this project, were demonstrated through the assembly of a convenience can inside a stainless steel primary can. An assembled convenience can is a hermetically sealed canister that contains Plutonium that has been converted to plutonium metal or a mixed oxide (MOX) fuel. The convenience can, when full, weighs approximately 4.8 kg and the complete assembly weights 5.1 kg. For the demonstration, the clearance for the convenience can inside the primary can is less than 1.2 mm and the clearance for the lid on the primary can is less than 0.55 mm.

Results

Assembly Of Manipulator Using Quick Connects

The demonstration of the quick-connect system displayed how the simplicity of these connections allows a manipulator to be assembled/disassembled in a matter of minutes. Since the quick connect is a very accurate interface, a manipulator can be assembled external to the glovebox and then fully qualified before it

is disassembled and passed into a glovebox. The demonstration of the quick connect feature is captured a series of photographs, documenting the activity, presented as Figure 5.

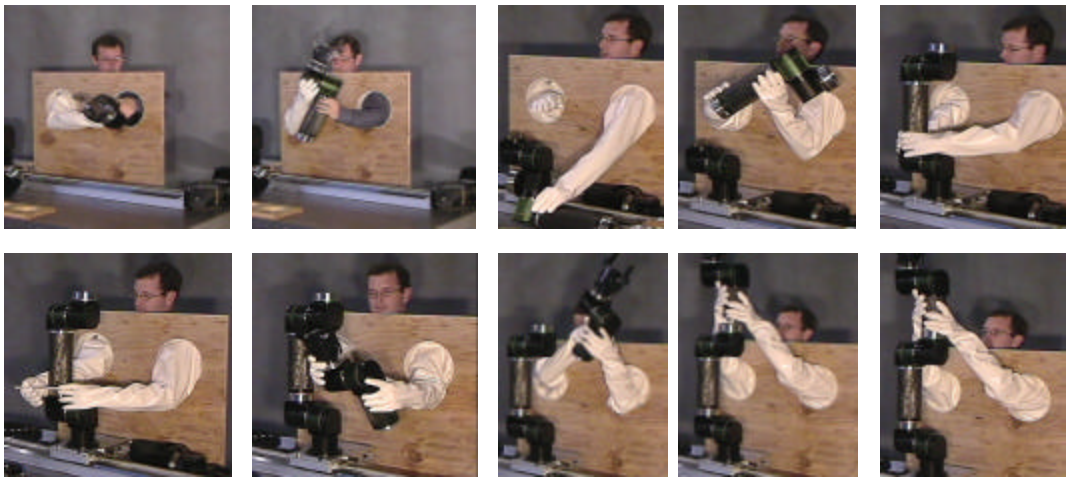

Figure 5. Modular manipulator assembly sequence inside a simulated glovebox.

Assembly of A Convenience Can Inside A Primary Can

Two demonstrations were performed; one with an empty convenience can using a four degrees-of-freedom (DOF) system consisting of ARM20s and one with a full can weighing 4.8 kg using a 4 DOF system comprised of ARM32s for the lower two joints and an ARM20 for the distal joint. Figure 6 shows the sequence of the first manipulator assembling the canisters and then moving the complete assembly.

A jig was manufactured for positioning the convenience container, primary container and lid. This test not only demonstrates the repeatability of the manipulator, but also the agility of the kinematics of this configuration.

Observations resulting from the testing indicate that error handling at the system level need to be handled in a methodical manner such that the system does not sporadically shut down. The manipulator performed exceptionally smoothy once the system controller was upgraded to a new version that eliminated program errors associated with an earlier version.

Conclusions

The successful demonstration of the modular technology developed under this project is a significant engineering achievement. Five technology advancements that were addressed in the original proposal were demonstrated by modular robotics: 1) Increased net payload to weight ratio; 2) Smaller umbilical cords; 3) Capacity for customization and reconfiguration; and 4) Easily repairable or replaceable components. In addition, the system's ability to be introduced through a glove port into existing gloveboxes without compromising personnel safety or automation features was demonstrated. Videotape records of the demonstrations were taken and are available upon request.

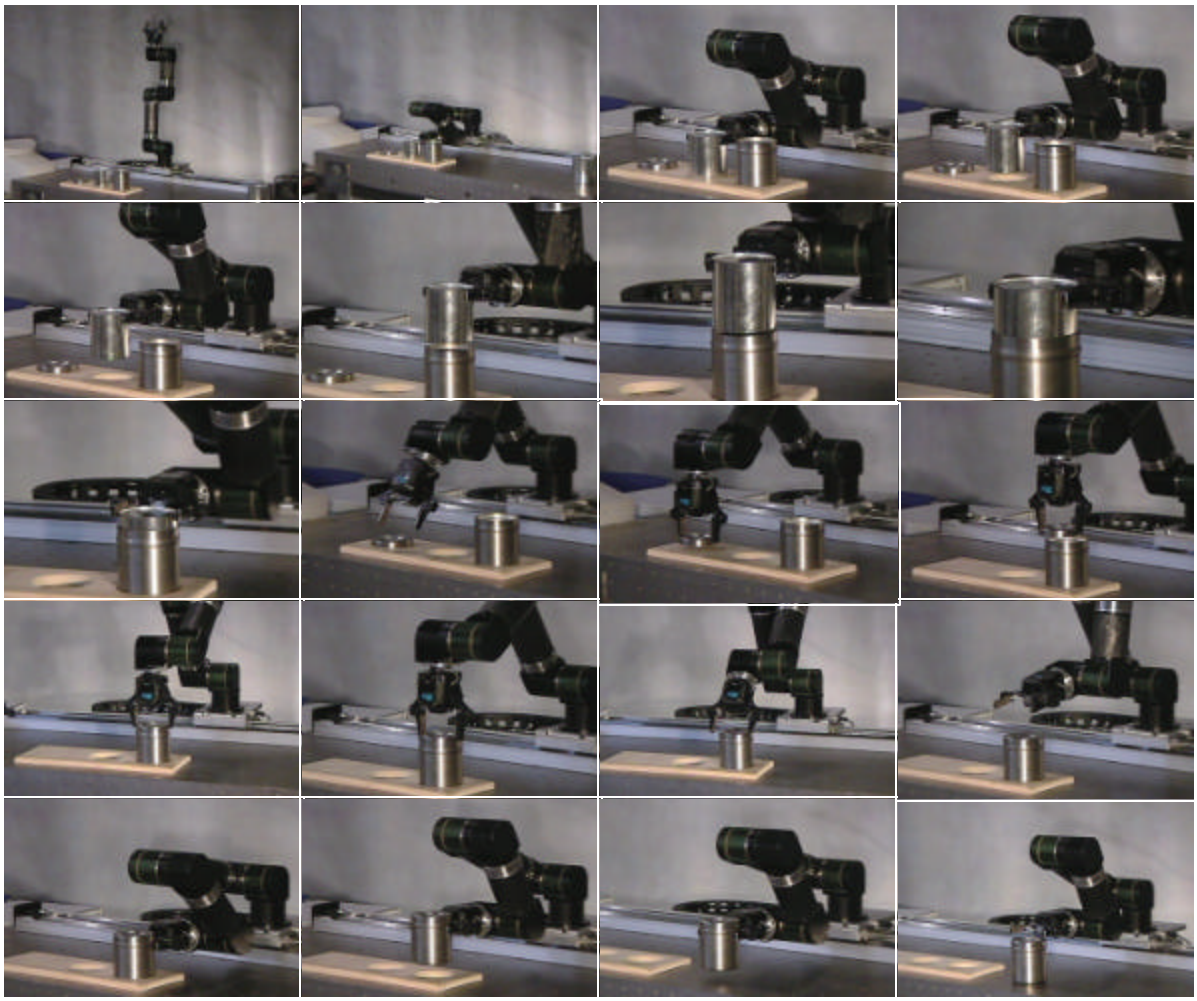

Figure 6. Modular manipulator assembling plutonium canisters.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

Manual Handling

The baseline approach for most material handling operations in a glovebox is manual handling through lead-lined gloves, as show in Figure 7 below (US DOE 1991). The primary drawback of manual handling is risk of exposure to radiation. Although the glovebox is designed to shield workers from radiation and contain the radioactive and hazardous materials, workers are still chronically exposed to small amounts of radiation and are at a higher risk for acute accidental exposure. In addition to the health risks, manual handling is an inefficient method for materials handling inside a glovebox. Automation of glovebox tasks with robotic equipment will reduce worker exposure and increase process efficiency.

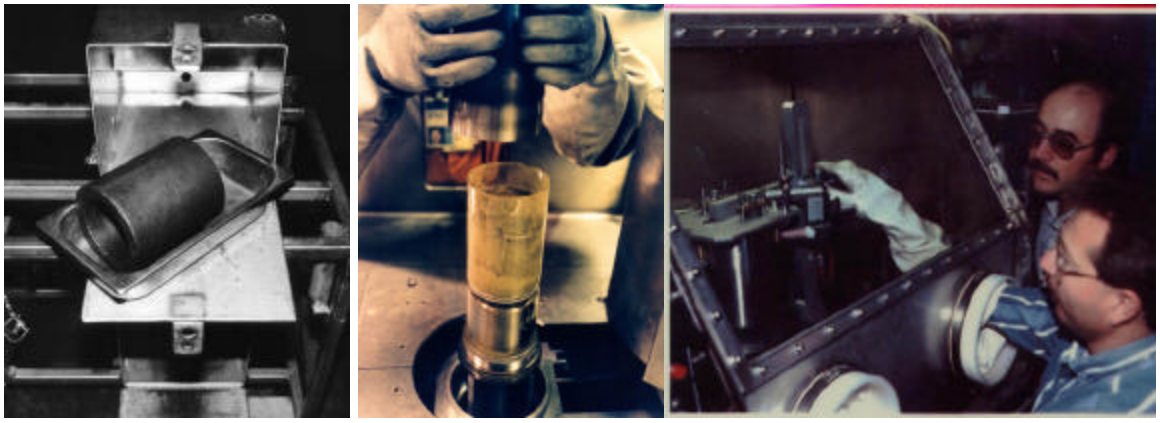

Figure 7: Insertion of MOX (left) into convenience can (center) and primary can (right).

Commercial Robotics

At LANL, a FANUC Robotics, LR-Mate 100i™ robot is utilized in an automated cell for the ARIES demonstration line (US DOE 2000). In this glovebox, LANL is combining two operations: welding and electro-decontamination of the material container. The system utilizes two LR-Mate 100i™ robots, one on the 'hot' side and one on the cold side (see Figure 8). The LR-Mate 100i™'s specifications are shown in Table 2 in Section 2. This robot is traditionally used for parts loading operations. While not ideal for the task at hand, it is presently the best commercially available option. The biggest obstacle associated with using this manipulator for glovebox automation is maintenance and repair within a glovebox. Even a task as simple as removing the cap from the grease zerk fitting becomes nearly impossible with gloves. Consequently, very few failures will be repairable inside the glovebox, and hence, the entire LR-Mate is viewed as a disposable unit. This creates significant challenges in several areas: 1) Removal and replacement of the manipulator, 2) Disposal of the failed manipulator and 3) Calibration of the new manipulator. After significant effort, LANL and SNL have devised a clever system by which a failed LR-Mate may be lowered down through a large portal in the glovebox into a bag and drummed for disposal. This system utilizes a linear guideway system to prevent Plutonium spillage due to the robot tipping over. The resulting operation is elaborate and requires time and care to perform. Despite the novel approach, it still has the additional disadvantage in that it cannot be retrofitted to existing gloveboxes. The LR-Mate's encoders use a battery located in the base to backup and maintain factory calibration. This battery must be removed during the installation of the manipulator into the glovebox causing the system to loose its factory calibration. Furthermore, the LR-Mate's payload capacity is inadequate to address the needs of APP.

Custom Robotics

Custom robotics is also an option for automation of various EM activities. While fully custom systems can be designed and built for a specific purpose (Dennison et. al. 1995, US DOE, Weapons Complex Monitor 1998), these robots are expensive to design, build and maintain compared to commercial robots. Maintenance of custom robots may also be slow if custom parts must be fabricated.

Figure 8. Two LR-Mate 100i^{TM}''s operational in the LANL ARIES glovebox (left), and LR-Mate 100i^{TM} viewed from inside of glovebox (right).

Technology Applicability

The advantages of modular robotic manipulators apply not only to globebox applications, but to a wide variety of EM applications. Examples include dual-arm robots for Deactivation and Decommissioning (D&D), manipulators for sorting through mixed waste, and systems for remote characterization and sampling. Many of these tasks are of human scale and could easily be addressed with manipulators built from the currently available sizes of actuator modules. Other operations such as heavier duty D&D tasks would require robots built from one or two larger sizes of actuator modules in order to wield large power tools and move heavy pieces of structure. This architecture has been designed to support this expansion.

Patents/Commercialization/Sponsor

Multiple invention disclosures have been filed for a patent. At the time of the publication of this ITSR, the patents currently have the status of “Patent Pending” and are awaiting approval for filing.

SECTION 5
COST

Methodology

The following cost analysis includes a comparison of the baseline method of manual handling in a glovebox to three robotic automation technologies; the modular manipulator, the commercially available Fanuc LR Mate 100i™ robot, and a custom-built robot. The analysis is based on glovebox plutonium conversion operations such as that demonstrated at Los Alamos using ARIES and proposed at Savannah River's PIP. The goal of the analysis is to compare the cost associated with implementation of the automation technologies to the benefit of reduced worker exposure to radiation.

The cost analysis has three steps: First, the cost benefit associated with reducing a worker's annual radiation dose is addressed. Second, the life-cycle costs for three automation technologies are calculated and applied to various operational scenarios. Finally, the cost savings determined in step one is compared against the life-cycle costs for each of the technologies. In the end, the cost benefit from automation can be evaluated and the most cost-effective technology can be determined. The implementation costs for the three automation technologies are fairly straightforward, while the cost savings from reducing a worker's radiation dose is more difficult to quantify. For the latter, accepted values that quantify cost savings from reduced worker exposure to radiation will be utilized. A detailed discussion of the occupational health and safety advantages of automating glovebox operations is provided in Section 6.

Cost Analysis

Cost Savings from Reduced Radiation Dose

The greatest benefit of robotic automation for handling radioactive and hazardous materials is in terms of reduced occupational safety and health risk. For the glovebox processes described in this report, automation technologies allow workers to be moved away from the hazard, which translates to reduced worker exposure to radiation. In terms of quantifiable cost savings, reducing radiation exposure minimizes the costs associated with replacing workers who have accumulated thier annual radiation dose limit. The costs associated with replacing a worker typically include such things as training a new worker and paying the worker that has "dosed-out" to do an alternative task. The estimated cost savings from reduced worker exposure to radiation varies based on site-specific conditions, but has been estimated as high as $30,000 per person-rem per year (Milham 2001). LANL has developed guidance based on cost-risk-benefit to assist site decision-makers in determining what is a reasonable cost for reducing a workers cumulative radiation dose. This guidance (Laboratory Procedure 107-16) states that $2,000 can be spent to avoid a person-rem of annual dose for individuals that have doses under two-thirds of the prestated, facility-wide, administrative control level. If individuals have an annual dosage of greater than two-thirds of the administrative level, then up to $10,000 can be spent per person-rem avoided (US DOE LANL 1998). The guidance is based on cost-risk-benefit, so for the purposes of this cost analysis, these figures will be considered as equivalent to cost savings from reduced exposure. For this analysis, it is assumed that half the personnel will fall in the category of "below two-thirds of the administrative level" and half of the personnel will be considered "above two-thirds of the administrative level". This will effectively present a cost savings of approximately $6,000 per person-rem eliminated. At LANL, the maximum annual dosage per worker is presently set at 2 rem with anticipation of reduction to 1 rem.

As a point of clarification, the approach discussed above is just one method of evaluating the cost savings from reduced exposure to radiation. It does not consider many other "real" monetary costs from exposure to radiation, such as the costs associated with adverse health affects. Although these costs are real, they are difficult to quantify and are beyond the scope of this analysis.

For the purposes of this cost analysis, it is assumed that automation of glovebox operations will reduce worker exposure by 50 percent. This is a reasonable estimate for this analysis, but a more detailed evaluation of a specific task may provide a more accurate value. The actual level of exposure reduction is a

critical value in determining cost savings. Estimated cost savings, based on a 50 percent reduction in exposure, applied to the plutonium conversion processes at LANL and SRS are provided in Table 3 below. The table includes the estimated worker exposure for three different scenarios: LANL's ARIES demonstration line; and two different proposed options at SRS. The SRS-Option 1 includes pit disassembly and plutonium immobilization; and SRS-Option 2 includes disassembly with a portion of the plutonium converted to MOX fuel and the remaining portion immobilized. Table 3 includes the number of workers for each process, the average worker exposure per year, and the total estimated radiation dose to all workers. The table also includes the total worker dosage based on a 50 percent reduction in exposure and in the far right column, the projected cost savings from reduced exposure.

Table 3. Estimated cost savings from reduced worker exposure to radiation.

Process	No. of Workers	Average worker exposure (m-rem/yr)	Total Worker Dosage (rem-person/year)	Reduction in Worker Dosage (50%) (rem-person.year)	Annual Cost Savings ($) Based on Reduced Exposure
LANL	120	1,250	150[1]	75	$450,000
SRS-Opt 1	674	618	410	205	$1,230,000
SRS-Opt. 2	991	566	561[2]	281	$1,683,000

[1]US DOE Office of Fissile Materials Disposition
[2]US DOE Office of Federal Register

Life-Cycle Costs for Automation Technologies

The life-cycle costs for a modular system, a Fanuc LR Mate 100i^{TM}, and a custom robotic system (designed by DOE personnel) were estimated for this analysis. The life-cycle cost for each technology includes the following cost elements: capital equipment; modification of the glovebox to accept the manipulator; installing the manipulator into glovebox; and calibration of manipulator inside of glovebox. The life-cycle scenario also assumes the unit will require repair once during the one-year life cycle. In the case of the LR-Mate 100i^{TM}, the unit is not repairable inside the glovebox and the unit is considered to be a disposable item (McKee 1998 and Turner 2001), rather than a maintainable piece of equipment. Therefore, a failed joint in the LR-Mate 100i^{TM} will result in removal of the unit from the glovebox, disposal of complete manipulator, and installation of a new manipulator, which includes capital cost, installation, and recalibration. This process is estimated to take six days. A modular manipulator, on the other hand, can be broken down inside the glovebox and the failed joint removed through a simple procedure as shown in the previous section easily taking less than one-man day. Thus, only the broken component will require disposal, as opposed to a complete manipulator. The custom robot is also considered to be repairable inside the glovebox. The life-cycle cost is based on the assumption that the manipulator will be removed from the glovebox and disposed at the end of its useful life. For the purposes of this analysis, the life cycle of all the manipulators is assumed to be one year. Actual lifecycles are dependent on the conditions inside the glove box, specifically radiation levels. Because of the short life-cycle, the time value of money was not considered in the analysis. Table 4 presents the estimated life-cycle cost for a custom manipulator, a LR-Mate 100i^{TM} and a 4 DOF modular manipulator system similar to that shown in Figure 1. The cost analysis is based on the following additional assumptions:

- The modular manipulator using components similar to the ones developed under this contract costs $120,000
- One custom manipulator takes three man-years to design and build (6,000 man hours) at a labor cost of $117/man-hour (Dyches et.al. 1999), for a total cost of $702,000 in labor and a material cost of $75,000
- Additional custom manipulators of like design can be produced at a cost of $112,400 each ($75,000 material cost plus 8 man weeks for assembly)
- The custom manipulator is similar to the modular manipulator in size and specifications.
- The disposal volume of the Fanuc LR-Mate 100i^{TM} is approximately 0.15 m^3
- The disposal volume for an ARM module, or joint on custom robot is 0.002 m^3
- The disposal volume of the entire ARM unit or custom robot is .075 m^3 (not including the linear track)
- The linear track for the modular manipulator is not disposed at the end of the life-cycle

- The contaminated equipment is disposed as a transuranic (TRU) waste and disposal costs range from \$35,000 to \$100,000/m^3 (Schaade 1998, US DOE, LANL 2000) The median value of \$67,500/m^3 was used in the estimate.

Table 4: Comparison of life-cycle costs for glovebox manipulators

Description	**Custom Robot**		**LR-Mate 100*i*™**	**Modular Manipulator**
	First Robot	Addit. Robots		
Initial Cost	\$777,000	\$112,440	\$50,000	\$120,000
Glovebox Customization	\$9,360	\$9,360	\$37,440	\$9,360
Place Manipulator in Glovebox	\$936	\$936	\$5,616	\$936
Calibrate Manipulator	\$234	\$234	\$1,872	\$234
Repair Manipulator Joint (equipment cost)	\$35,000	\$35,000	\$50,000	\$15,000
Remove and Replace Joint	\$1,872	\$1,872	\$11,232	\$1,872
Place Manipulator in Glovebox	\$0	\$0	\$5,616	\$0
Calibrate Manipulator	\$234	\$234	\$1,872	\$234
Dispose of Broken Joint	\$135	\$135	\$10,125	\$135
Remove Manipulator	\$936	\$936	\$5,616	\$936
Dispose of Manipulator	\$5,062	\$5,062	\$10,125	\$5,062
Total Life-Cycle Cost	**\$830,769**	**\$166,209**	**\$189,614**	**\$153,769**

Based on the results presented in Table 4, the modular manipulator has the lowest life-cycle cost. Compared to the Fanuc LR- Mate 100i™, the modular manipulator's ease of placement into the glovebox and repairability inside the glovebox makes up for its higher initial capital cost.

To apply the life-cycle costs presented in Table 4, to the three different plutonium extraction processes described (LANL, SRS-Option 1 and SRS-Option 2), the life-cycle costs above must be multiplied by the number of manipulators needed for each process. Each LANL plutonium conversion line will require two manipulators: one for the pit disassembly and one for the canning and measuring process. The SRS Option 1 will utilize a total of four manipulators in two lines to perform the pit disassembly and immobilization. SRS Option 2 will utilize a total of six manipulators in two lines to perform pit disassembly, pit immobilization, and MOX conversions.

Table 5 includes the life-cycle costs for the three automation technologies applied to the three scenarios described above and also includes the projected cost savings from reduced radiation dose presented in Table 3. Based on this analysis, two of the three automation solutions show considerable positive net savings. The custom robot shows positive cost savings for only the largest scale application (SRS Option 2). As this analysis shows, the modular technology achieves at least \$100,000 in cost savings for almost all types of implementations and can achieve a total savings in excess of \$700,000 if implemented on a large scale basis, as in SRS-Option 2.

Table 5: Estimated cost savings from implementation of automation technologies.

Plutonium Reduction Method	**Life-Cycle Cost**	**Cost Savings (from Table 3)**	**Net Savings/Loss(-)**
ARM Modular Manipulator			
LANL (2 Manipulators)	\$307,538	\$450,000	\$142,462
SRS Option 1 (4 Manipulators)	\$615,076	\$1,230,000	\$614,924
SRS Option 2 (6 Manipulators)	\$922,614	\$1,683,000	\$760,386
Fanuc LR-Mate 100i™			
LANL (2 Manipulators)	\$379,028	\$450,000	\$70,972
SRS Option 1 (4 Manipulators)	\$758,056	\$1,230,000	\$471,944
SRS Option 2 (6 Manipulators)	\$1,137,084	\$1,683,000	\$545,916
Custom Robot			
LANL (2 Manipulators)	\$996,978	\$450,000	\$-546,978
SRS Option 1 (4 Manipulators)	\$1,329,396	\$1,230,000	\$-99,396
SRS Option 2 (6 Manipulators)	\$1,661,814	\$1,683,000	\$21,186

Cost Conclusions

The cost analysis presented here reveals that automation of plutonium conversion operations does have cost advantages. Although not exhaustive, this analysis justifies the automation of glovebox operations and provides insight regarding the cost advantages of the modular manipulator compared to other technologies. The cost savings presented are strictly based on cost savings from reduced worker radiation dosage and do not consider such things as increased process efficiency and rate of production.

A number of conclusions can be drawn from the comparison of the three different robotic automation technologies. First, custom robots are expensive to design and produce. Although the life-cycle cost for the custom robot is conceptual, one can understand why a custom robot would cost several times more than an approach that takes advantage of mass production. Second, the Fanuc LR-Mate 100i™, has an low initial cost, but it is not reconfigurable, limiting its application. Further, its design is not conducive to repair inside the glovebox. The modular-manipulator is similar to a custom robot in that it can be configured to suit a specific application. Yet, it is similar to a commercial robot with respect to cost because the modular components are designed to be “off-the-shelf”. The compact modular design and quick connections eases repair and maintenance inside the glovebox, which results in cost savings.

Automation of glovebox activities is integral to reducing worker exposure using the ALARA concept. Whether or not the implementation costs are “reasonable” for achieving a certain reduction in exposure (or risk) is a key factor in the decision making regarding implementation. Based on the analysis here, implementation of the Modular Manipulator for automation of glovebox plutonium conversion activities does provide significant risk reduction at a “reasonable” cost.

SECTION 6
OCCUPATIONAL SAFETY AND HEALTH

Comparison with Baseline and Alternative Technologies

The primary purpose of automating glovebox operations with robotics is to reduce worker exposure to radiation. Robotic automation reduces worker exposure by moving the worker away from the radiation source and reducing the time spent in proximity to radiation. The baseline method is manual handling through lead-lined gloves. Although the glovebox provides shielding and containment, chronic exposure from attenuated gamma radiation and/or air leakage does occur. Under the baseline approach the worker's close proximity to the radiation increases risk of exposure. In the cost analysis presented in the previous section, ARM Automation estimated that a 50 percent reduction in overall worker radiation dose could be achieved from automation of plutonium conversion operations. Actual reductions in exposure need to be confirmed and will vary depending on task-specific conditions.

As with most mechanical equipment, robotic systems require maintenance and repair. In the case of robotic automation of glovebox activities, this requires workers to perform maintenance and repair through gloves in close proximity to the glovebox. The modular manipulator is designed to make maintenance and repair as easy and worker-friendly as possibly, ultimately reducing time spent close to radiation sources. The modular approach to robotics has health and safety advantages over non-modular robotics, like the Fanuc LR Mate 100i™. Removal of the Fanuc LR-Mate 100i™ and re-installation would take much longer than replacing a joint on the Modular Manipulator.

Required Safety and Health Measures

Automation using robotics does create some new potential hazards not present with the baseline. The most significant potential hazard is from the manipulator unintentionally hitting or damaging the walls of the glovebox, thus comprising the integrity of the glovebox. This occurrence is mitigated through provisions in the computerized control system. The power supply for the manipulator supplies 300VDC power; therefore an electrical hazard does exist, but it can be addressed through standard industrial safety practices. The modular manipulator will require certification by the Defense Nuclear Facilities Safety Board prior to actual deployment in a glovebox.

Although the manipulator is designed for ease of maintenance inside the glovebox, safe procedures must be developed for the activities. The procedures should be specific to the setting in which the manipulator is used. The modular components are designed to allow easy passage of through glove-ports, but safe procedures must be devised and followed to avoid contamination or exposure.

Safety and Health Lessons Learned from Demonstrations

Health and Safety issues were integrated into the development of the technology. The first option for the quick-connect system was a band-type connection. This option was effective, but was not selected because it had pinch-points, which are unacceptable in the glovebox environment. The current quick-connect system does not have problems with pinch-points and delivers acceptable performance characteristics.

SECTION 7
REGULATORY AND POLICY ISSUES

Regulatory Considerations

Before the modules can become a commercial product that can be purchased off-the-shelf, they will need to undergo more system-level testing in real applications. Along that line, ARM is pursuing opportunities to advance the technology by getting systems into the University of Texas at Austin Robotics Research Group (UT-RRG), LANL, and SNL for further testing. If these knowledgeable groups are able to secure funding to perform outside testing, the overall reliability of these systems will be improved. This testing will be necessary to get the modular robotic technology approved by the Defense Nuclear Facilities Safety Board for glovebox use. Certification by the DNFSB will be crucial in the integration of modular robotics into glovebox operations.

Secondary waste streams generated by modular robotics include failed modules. While these modules will need to be decontaminated and disposed after operation in a 'hot' box, they will generate significantly less volume than non-modular alternatives.

Risks, Benefits, Environmental and Community Issues

- The benefits associated with reduced worker exposure to radiation afforded by the modular manipulator technology far outweigh the risks associated with maintenance of the equipment or potential malfunction.
- Public/community acceptance of the technology is likely to be favorable considering the occupational safety and health benefits.
- Implementation of the technology is in keeping with DOE ALARA policy.
- Life cycle costs for the technology are acceptable considering the savings from reduced worker radiation dose.
- The benefits of the technology can be easily understood by the public (i.e. robots will handle radioactive materials rather than humans, thus reducing exposure).
- Automation of glovebox activities will not significantly reduce required labor force for glovebox operations, but a more technically skilled worker will be required to operate and maintain the automation equipment.

SECTION 8
LESSONS LEARNED

Implementation Considerations

Industry and the DOE are increasingly interested in the potential advantages of modular robotics to address the DOE's automation technology needs. The modular manipulator developed under this project has demonstrated many desirable traits well suited to DOE glovebox applications and other automation needs. At the conclusion of this project, the technology was not ready for commercialization, but is at a prototype-scale. Successful commercialization of the technology and acceptance into DOE market will require further qualification and beta testing by the site personnel.

Technology Limitations and Needs for Future Development

Although the technology is fully functional in the hands of an experienced robotics engineer, the system requires additional development prior to commercialization. The area requiring the most development is system level software. Originally, ARM had anticipated that the software purchased off-the-shelf would be sufficient in controlling the manipulator. However, the interface between the system level software, which was designed for analog amplifiers, and the SERCOS communication system took more effort than anticipated. As a result, ARM has not significantly developed the error handling capability of the system level software. Some additional development is also required at the component level. Radiation hardness is another area of investigation for the system. ARM has done some preliminary investigation into the radiation hardness of some of the components, but has not done a complete study of the system

Component Development

There are several components of the system that require improvement. These include: the error handling process of the system controller, the noise immunity of the communications signal, the corrections to the PSI and CCI boards, degradation of actuator brake material, the implementation of a position loop in the DISC™, and the motor winding connections of the ARM32. ARM Automation has conceptualized solutions to address many of these issues and plans to implement them in future system redesigns.

Radiation Hardening

The radiation levels in many of the DOE applications range from a few mRad/hr to approximately 8,000 Rad/hr in canyon remediation applications. For the most part, the modular actuators were designed so components with increased radiation hardening could be substituted at a higher cost. The current system is estimated to withstand a radiation dose of 25 kilo-Rad. Radiation hardened components have been identified for mechanical system, wiring, electronic sensors and electronic controllers. It is estimated that the DISC™s are tolerant to at least 3 KRad (Si) although conclusive results can only be obtained through actual testing. ARM is presently talking with Dr. James Tulenko, of the University of Florida's Department of Nuclear and Radiological Engineering, about performing future radiation tests on the DISC™ electronics. This is the only conclusive method to arrive at evidence as to actual level of radiation-tolerance the DISC™s.

Ongoing Development

In an effort to further the modular approach to robotic automation within DOE-EM, a new project is underway for automated characterization and mapping of contamination. Under a SBIR grant (#DE FG03-00ER 82950.000), this modular system is being used to create a series of robotic positioning devices for delivering and locating the sensor head assembly of the 3-D ICAS characterization system. This characterization system provides comprehensive, real-time contaminant analysis and mapping in a portable package. Through the use of ARM's modular robotic system, a series of custom light-payload, long-reach manipulators will be constructed to locate this sensor system much more effectively, making possible in-situ, real-time analysis of site contamination and location. At present, ARM is working with candidate

facilities to locate a specific deployment opportunity for this combined system and expects to begin testing in 2002.

APPENDIX A
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APPENDIX B
ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
ALARA	As Low As Reasonably Achievable
ANL	Argonne National Laboratory
ARIES	Advanced Recovery and Integrated Extraction System
ARM	ARM Automation, Inc.
CCI	Control and Communications Interface
CE	Conformité Européenne
CFM	Cubic Feet per Minute
CODE	Cimetrix Open Development Environment
D&D	Deactivation & Decommissioning
DC	Direct Current
DISC™	Distributed Intelligent Servo Control
DOE	Department of Energy
DOF	Degree Of Freedom
DP	Defense Programs
EM	Environmental Management
E-Stop	Emergency Stop
FA	Focus Area
FSMA	Fiber Sub Miniature Assembly
HAN	Hanford Site
I/O	Input/Output
IDE	Integrated Drive Electronics
kg	Kilogram
LANL	Los Alamos National Laboratory
LP	Laboratory Procedure
LVDS	Low Voltage Differential Signaling
MC	Momentary Closed
MD	Materials Disposition
MEI	Motion Engineering, Inc.
MOX	Metal Oxide
MW	Mixed Waste
N	Newton
NC	Normally Closed
NO	Normally Open
P	Pitch
PC	Personal Computer
PIP	Plutonium Immobilization Project
PSI	Power and Sensor Interface
PSSI	Power Supply and System Interface
R	Roll
RFETS	Rocky Flats Environmental Technology Site
RPM	Revolutions Per Minute
SERCOS	SErial Real-time Communications System
SNL	Sandia National Laboratory
SRS	Savannah River Site
SVGA	Super Video Graphics Array
TCP/IP	Transmission Control Protocol/Internet Protocol
TID	Total Ionizing Dose
TRUW	TRansUranic Waste
UT-RRG	The University of Texas at Austin Robotics Research Group
W	Watt