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Title:

Robotics for Nuclear Material Handling at LANL: Capabilities and Needs

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Intended for:

2009 ASME IDETC/CIE Conference
San Diego, CA
August 30-September 2, 2009

Los Alamos
NATIONAL LABORATORY
EST. 1943

09-
-01157

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Proceedings of IDETC'09:
ASME 2009 International Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
San Diego, California, August 30-September 2, 2009

DETC2009-86777

ROBOTICS IN NUCLEAR MATERIALS PROCESSING AT LANL: CAPABILITIES AND NEEDS

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Abstract

Nuclear material processing operations present numerous challenges for effective automation. Confined spaces, hazardous materials and processes, particulate contamination, radiation sources, and corrosive chemical operations are but a few of the significant hazards. However, automated systems represent a significant safety advance when deployed in place of manual tasks performed by human workers. The replacement of manual operations with automated systems has been desirable for nearly 40 years, yet only recently are automated systems becoming increasingly common for nuclear materials handling applications. This paper reviews several automation systems which are deployed or about to be deployed at Los Alamos National Laboratory for nuclear material handling operations. Highlighted are the current social and technological challenges faced in deploying automated systems into hazardous material handling environments and the opportunities for future innovations.

1. INTRODUCTION

At Los Alamos National Laboratory (LANL), nuclear materials are processed for a number of purposes. Weapons components are manufactured, samples for materials science experimentation are prepared, radio-isotopes for medical diagnostics are produced, heat sources are developed for power generation in deep space probes, and decommissioned weapons components are reprocessed into forms suitable for international inspection, long-term storage and/or re-use as mixed-oxide (MOX) reactor fuel. A constant within all of these activities is the manual handling of nuclear materials in what can be characterized as a hazardous or extreme environment.

The materials are handled and processed within enclosures, called gloveboxes. A glovebox, such as that shown in Fig. 1, provides environmental isolation and containment of the materials and processes. Manual access is possible through several ports with attached gloves through which workers must conduct their work. The only visual access is through small windows in the sides of the glovebox. The loss of manual dexterity caused by the gloves, and the issue of vision and parallax effects caused by the windows dramatically increase the time required to accomplish even simple tasks.

Figure 1. A typical LANL glovebox. Note the connecting ports on the near end of the glovebox. These ports allow gloveboxes to be connected into lines and materials to be passed through airlocks between gloveboxes with different environments.

However, the most significant concern is the Occupational Radiation Exposure (ORE) incurred by the operators. While the stainless steel composition of the gloveboxes, as well as additional lead shielding reduces the accumulated radiation dose, workers accumulate a radiation dose during processing and handling operations. Current regulations limit the dose of Department of Energy (DOE) workers to less than 5 rem per year [LANL, 2008]. While these limits are considered more than adequate to prevent long-term health affects, the reduction of ORE is an ongoing consideration and justification for the deployment of automation systems.

2. NUCLEAR MATERIAL PROCESSING

Gloveboxes are connected to form processing lines. Where each glovebox hosts one or more manufacturing processes, a glovebox line acts like a manufacturing production line. The Advanced Recovery and Integrated Extraction System (ARIES) is a typical example of a glovebox line at LANL. ARIES also has evolved into a demonstration of the potential of glovebox automation at LANL.

The ARIES line consists of five gloveboxes connected through a common spine and an external non-glovebox operation. This design, as opposed to an end to end connection, has enabled the ARIES line to be modified and upgraded over the years with new processes and technologies while minimizing the disruption to the remaining processes. More detail on the processes on the line is given in Fig. 2.

NDA Module - Performs a non-destructive assay measurement on the cans produced by ARIES (Not a glovebox operation).

Electrodecon Module - Decontaminates and leak checks the cans produced by ARIES.

Hydride Module - Performs a hydride/dehydride process on the nuclear materials.

Disassembly Module - machines nuclear components into their constituent parts.

RIPS Module - automated canning and decontamination module.

Direct Metal Oxidation Module - produces oxides from nuclear material components.

Conveyor, Drop Box, Hood - links the individual gloveboxes to each other and the facility.

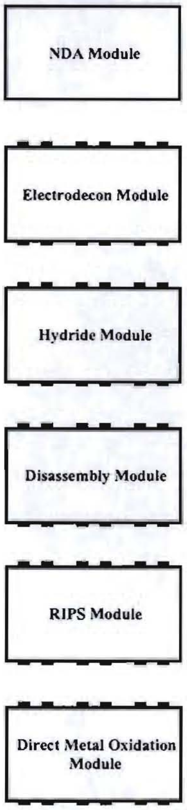

Figure 2. The ARIES Glovebox Line.

2.1. TASK STUDIES

The manual operations in the ARIES line were studied in 1999 by The University of Texas at Austin. The ARIES line was selected as a typical glovebox line at LANL. Each operation was documented and classified into six categories: movement, orientation, sensing, inspection, process control and other unclassifiable complex tasks [Turner, 1999]. A total of 58% of the operations in ARIES involved either moving an object from one location to another, or changing the orientation of an object at a location. These tasks are considered to be easily automated and represent a significant opportunity for a reduction in ORE if these manual operations are automated. The results of the task study are summarized in Table 1.

Table 1. ARIES Task Analysis Summary [Turner, 1999].

Classification	Percentage	Automation Potential
Movement	49.5%	High
Orientation	8.5%	High
Sensing	7.3%	Moderate
Inspection	2.7%	Low
Process Control	19.0%	Moderate
Other	13.0%	N/A
TOTAL	**100%**	

2.2. ENVIRONMENTAL CONSIDERATIONS

Individual glovebox operations pose different environmental hazards. Several processes are conducted under inert atmospheres (typically helium or argon), and even when air is used, it is typically a dry air box with the moisture levels significantly reduced. Consequently, the seals and electrical components of automation systems are subjected to an unusual environment. Seals may break down at an accelerated rate and electrical components may experience arcing problems. Consideration of both factors must be given during the design phase, although typically mil-spec components seem to prevent many of these issues.

The radioactive nature of the materials also can cause problems although the effects are often overstated. Except for a few applications, radiation hardened electronics are not necessary. The typical glovebox environment does not reach the radiation levels necessary to cause error in most electronic systems. However, as component size and the proximity to the materials decrease, there is an increased susceptibility. Small sensors in particular can have issues, although it is not always clear whether these issues are due to radiation. This is also not the case in hot-cell applications such as the processing of fuel rod materials [Heyward, 1990; Hintenlang, 1990; Cox, 1999].

Radiation also contributes to the deterioration of polymer and elastomer components such as seals, pneumatic tubing and electrical insulation. While hard data is not available concerning the failure rates attributable to these causes in ARIES, material degradation due to radiation effects is considered to be of significant concern.

Radioactive materials such as plutonium, which are handled in the ARIES glovebox line, also represent a particulate hazard. The decay energy of plutonium is sufficiently high that decays a few atoms below the surface produce dust particles. These plutonium particles spread as particulates and can cause excessive wear on mechanical components and affect electrical components such as microswitches and sensors.

Often chemical processes are a part of the glovebox lines. Corrosive chemicals and thermal hazards from furnaces can add additional requirements to automation systems that must operate in proximity to these processes.

Finally, the isolated glovebox environment also introduces design challenges. Unexpected failures are undesirable and can significantly impact operations. Unfortunately, the reliability of early robotic systems was insufficient for glovebox applications, which delayed subsequent automation projects. In addition, the limited accessibility of equipment within a glovebox makes maintenance and repair operations on automation systems extremely challenging. Therefore, maintenance and failure recovery become essential design considerations for any glovebox automation system.

2.3. FEATURED APPLICATIONS

Two LANL automation applications are presented in subsequent sections. The first is the ARIES line, which has been in operation for the last decade includes several automation projects developed at LANL. It clearly shows the advances made in automation technologies over the last decade and a half. The second application is a Sphere Cleaning Robotic System - which is currently under development for future deployment. This system is built around a redundant 7-Degree-of-Freedom (DOF) manipulator.

3. AUTOMATION IN ARIES

The ARIES line has been a significant development opportunity for glovebox automation technologies. ARIES receives the cores of retired nuclear weapons, called "pits", separates the nuclear materials from the non-nuclear components, and converts the nuclear components into oxides, which are packaged according to the DOE 3013 packaging standard [DOE, 2004] into stainless steel containers. These containers are subsequently decontaminated, leak checked and released for a non-destructive assay to measure and characterize the material content of each container. These containers can be stored for up to 50 years, used in international treaty compliance, and eventually, the oxide materials contained within these containers can be transformed into MOX fuel for nuclear reactors. This process is schematically shown in Fig. 3.

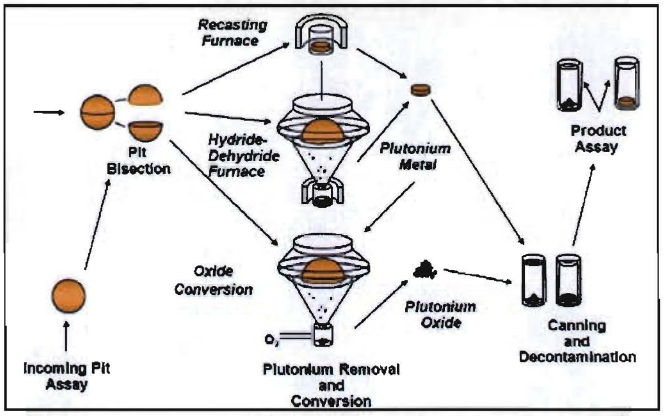

Figure 3. The ARIES glovebox line process. ARIES converts retired nuclear weapons into materials suitable for storage, inspection or reuse [McKee, 2008].

The Non-Destructive Assay (NDA) module and conveyor modules were the first modules within ARIES to be automated. Currently, automation systems are being added to the Disassembly Module (Pit-D) and the Robotic Integrated Packaging System Module (RIPS). RIPS represents the most complex automation system yet deployed within ARIES. These automation systems will significantly decrease the ORE of ARIES operators.

3.1. ARIES CONVEYOR SYSTEM

The ARIES conveyor system was the first portion of the ARIES line to be automated. Because it interacts with and provides material handling for every module on the line, the conveyor had the greatest potential for reducing manual operations. The conveyor is a custom-designed fixed-automation system that utilizes Thomson rails and standard industrial pushbutton/PLC controls. The conveyor has been in operation for over a decade, and in general, it works well. It provides a large improvement over the rope and pulley type conveyors used in several other glovebox lines at LANL.

The largest deficiency in the ARIES conveyor is maintenance. Although the system is maintainable, maintenance operations are often tedious and push the boundaries of what operators can do when working through glovebox gloves. LANL has applied the maintenance lessons learned on this conveyor to the design of several subsequent conveyor systems, especially the necessity for modularity and easily replaceable large components.

3.2. NON-DESTRUCTIVE ASSAY MODULE

The NDA module, Fig. 4, is built around a 3-DOF gantry robot. The NDA robot uses commercial x- and y-axes with a custom LANL-designed telescoping z-axis. This custom axis was necessary because of the limited clearance height for the system and the need to reach a container in the calorimetry system. The robot allows fully autonomous 24-hour operation of the NDA system and uses four instruments to measure the fissile content of material containers without the need for operator oversight.

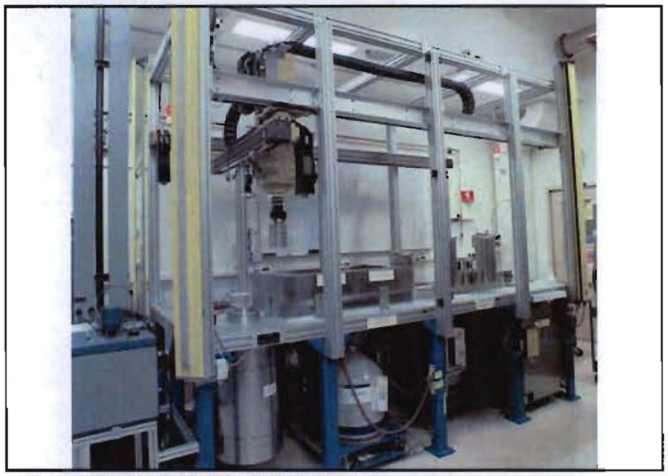

Figure 4. The ARIES NDA Module.

The NDA module uses three instruments to assay the packaged materials. The three instruments are a heat flow calorimeter with a gradient bridge design, a coaxial design gamma-ray isotope detector, and a neutron multiplicity counter (NMC). The NMC is capable of both passive neutron measurements, and active interrogation of nuclear material sources. NMC is the primary measurement method used in ARIES. All three of these instruments have been refined during the operation of the ARIES glovebox line [Wenz, 2008].

NDA was selected as the first process module to be automated for several reasons. First, it operates outside the glovebox environment and therefore enabled the robotic technology to be evaluated in a readily accessible and maintainable environment with minimal programmatic risk. Second, the tasks performed by the NDA module are highly repetitive and primarily involve the movement of well-defined objects between well-defined locations. Tasks of this type generally are easy to automate and serve as an excellent demonstration for the potential of automation. Finally, the measurement times involved with the three instruments are significant and thus it is highly desirable for NDA to operate around the clock and without immediate human supervision. Automation was able to meet these needs within and has contributed to the success of the NDA module. This success led to the decision to deploy additional automation systems within ARIES.

3.3. DISASSEMBLY MODULE

The robot used in the Disassembly module, Fig. 5, uses a gantry robot design similar to that used by the NDA module. The Pit-D robot consists of three commercial axes, and a custom LANL-designed 2-DOF wrist, shown in Fig. 6. Several grippers were also designed by LANL to handle the tooling and chucks for a custom designed Moore lathe and the components to be processed by the Pit-D module.

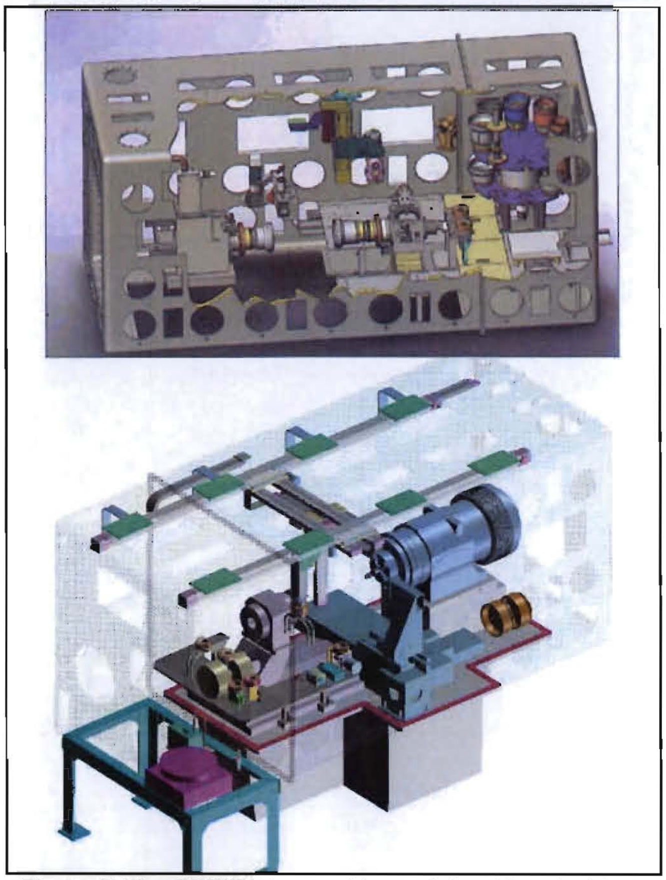

Figure 5. The ARIES Disassembly Module with and without the glovebox shown.

Unlike the NDA system, the Pit-D robot operates within a glovebox and consequently additional consideration was given to the maintenance needs and potential failure modes of the robot. Many of these potential events were explored through computer simulations before the design was completed [McQueen, 2001; Foster, 2001].

Simulations of the workspace properties of the robot were of particular importance in this module as the Pit-D robot shares its workspace with an automated Moore lathe and customized tool changer which add an additional 5-DOF to the system. Simulation allowed these systems to be placed in proximity to each other and to identify the potential collision locations early in the design process. In addition, all three automation systems share a common control system (an Aerotech U-600) whose operation was explored in simulation. An example of the simulations is shown in Fig. 7 [McQueen, 2001; Foster, 2001].

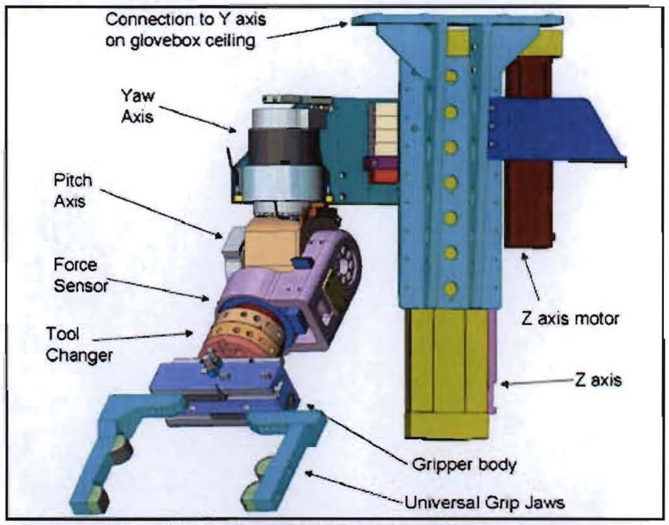

Figure 6. LANL Designed Pit-D wrist and gripper.

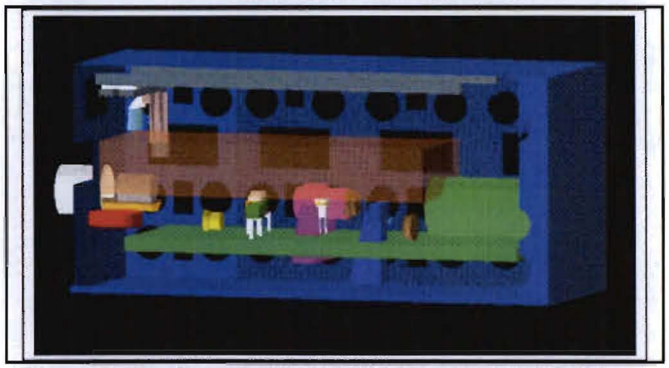

Figure 7. Simulations of the ARIES Disassembly Module.

Simulation also played a critical role in the installation of the Disassembly module. The automated version of this module was a system upgrade to the original ARIES glovebox line and replaced a previous system. Consequently, the new system and glovebox had to be moved into the facility and the room that contains the ARIES glovebox line and around various horizontal and vertical obstacles that lie along the installation route. Considering that the system and glovebox weighs several tons, provision also had to be made for the forklift to move it. As a consequence of these installation constraints, the Pit-D glovebox was designed in two pieces which were only assembled once both parts were in the module's final position. In places, the resulting clearance was less than 0.5 inches, but the use of simulations validated the move was feasible before the design was built. A view of the Pit-D glovebox during installation is shown in Fig. 8.

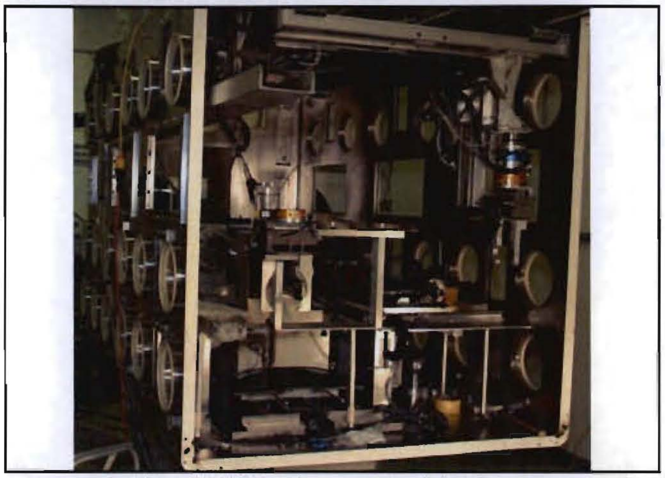

Figure 8. The ARIES Disassembly Module prior to the installation of the end cap.

Unlike the NDA robot, the Pit-D robot is designed to function as a semi-autonomous system. It operates in collaboration with and under the direction of human operators. Several common repetitive actions will be preprogrammed (i.e. retrieving and exchanging grippers), but many robot activities will be directed by the operator through manual controls. The vision of the operator is aided by the strategic positioning of several cameras within the glovebox. Because of the manual control of the robot, coupled with "macros" defining common tasks, this type of automation is considered to be semi-autonomous. The Pit-D module is currently being acceptance tested prior to being approved and certified for operation. It is expected that the Pit-D Module will achieve an order of magnitude ORE reduction [Brown, 2008].

3.4. THE RIPS MODULE

The RIPS module is more complex than either the Pit-D or the NDA modules. Like Pit-D, RIPS is contained within a glovebox which is divided into three separate compartments known as: the hot side, the cold side and the fluid processing side as shown in Fig. 9. Both the hot and cold sides of RIPS have their own 5-DOF Fanuc LR Mate 100i model robots. These robots are the first industrial class robots used to automate an ARIES glovebox.

The Fanuc robots are integrated with an automatic welding system, an electrolytic decontamination system, two separate leak-testing systems, and a radiation survey system. These additional systems add another 10-DOF of fixed automation components to the module and thus RIPS contains 20-DOF of automation. This is twice the automation complexity as Pit-D and nearly seven times that of NDA. Yet RIPS has the smallest footprint (40 square feet) of the automated ARIES modules. In fact, RIPS occupies a smaller footprint than either the NDA or Pit-D modules [Turner, 2008].

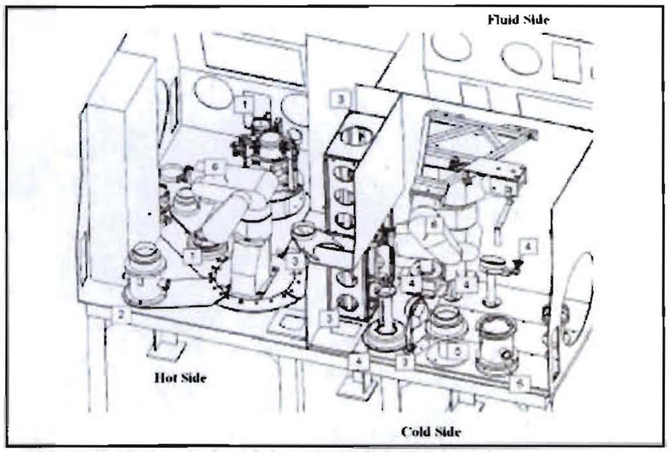

Figure 9. Schematic of the ARIES RIPS Module.

RIPS is designed for fully automated (but attended) operation. The operator can initiate system operations, and only have limited interaction (for instance visual inspection of the weld) during the entire operation. The system receives a crimped convenience can of fissile material in the hot side chamber of the glovebox (Fig. 10). The robot then places the convenience can in a stainless steel 3013 inner can. The inner can assembly is placed in the automatic welding system which welds the can under an inert helium atmosphere. The welded inner can is transferred to the hot leak check system which verifies that the weld hermetically seals the can. Then the inner can is transferred to the electrodecon chamber where the can is decontaminated electrolytically. Effectively, the process electropolishes the outer surface of the can, removing most of the contamination. The fluid processing chamber of the glovebox contains the necessary equipment to support the decontamination operations.

Figure 10. RIPS Hot Side Activities.

The electrodecon chamber also serves as an airlock between the helium-atmosphere of the hot side chamber and the air-atmosphere of the cold side chamber of the RIPS glovebox. Following decontamination, the cold side robot processes the welded inner can through a series of radiation surveys to determine the presence, amount and location of any removable or fixed contamination on the can's exterior. If the can passes the radiation survey, the system performs a second helium leak check to verify that the weld is intact. Once this cold leak check is complete, the can is released from RIPS (Fig. 11). Currently, the radiation survey is independently verified by a second survey performed by a radiological control technician (RCT), but the automated survey process may eventually eliminate the need for an independent RCT survey. If a process failure occurs, RIPS is capable of autonomous, semi-autonomous and/or manual fault recovery in collaboration with an operator.

Figure 11. RIPS Cold Side Activities.

Simulation was extensively used to design RIPS. Simulations studied the workspaces of the robots, the maintenance needs of the system, and alternative design configurations [Lumina, 1997; Turner, 2000]. The robots used in RIPS are commercial grade, unlike the customized systems used elsewhere in ARIES. The commercial robots are designed with expected lifetimes in excess of 20,000 hours. But, if replacement is necessary someday, the RIPS glovebox is designed to allow for either robot to be removed and replaced. These activities have been demonstrated both in simulation and during acceptance testing. It is even conceivable that these robots could be re-used in other glovebox applications. Because of the customized nature of their designs it is unlikely that either the NDA or Pit-D systems could be re-used.

The various subsystems in RIPS are interconnected through an internal computer network. Communications range from simple bitwise signals to TCP/IP enabled communications. This complex computer network limits the complexity of messages that can be passed between systems and thus limits the integration of sensor systems into RIPS. The lack of sensor feedback is a significant limitation in RIPS as well as the other automation systems currently deployed but may be remedied with the next generation of systems. Currently, the RIPS system has completed acceptance testing and is awaiting approval for operation.

4. AUTOMATED SPHERE CLEANOUT

In the past, spherical dynamic experiment containers used at LANL were manually cleaned at a specialized cleanout glovebox. This was a hazardous and tedious operation, often taking many months to accomplish. The ergonomics of the manual cleaning procedure were hard on the operators making it difficult to keep people. In addition, the manual process was not as thorough as desired. Several automated systems have been developed to address some of these problems.

4.1. A MECHANIZED CRAWLER

One of the most strenuous and tedious manual sphere cleaning tasks is brushing the interior walls of the sphere to remove fixed contamination. In the past, this was done by a worker using a brushing motor on the end of a long pole. Several years ago, a prototype mechanized crawler was developed to perform this operation. This crawler was designed for use as a platform to transport a motor operated wire brush around the interior surface of the test containers as seen in Fig. 12. The prototype unit used a commercially available magnetic crawler as the initial platform and then applied various design changes and upgrades to adapt the crawler to this specific application [Pittman, 2002]. Although the crawler worked well on pristine spheres, it would fall off the wall/ceiling of a sphere with large surface defects (potentially caused during the dynamic experiments). Also, the mechanized crawler only addressed the brushing operation. Therefore, a more complete automation solution utilizing a robotic manipulator was pursued.

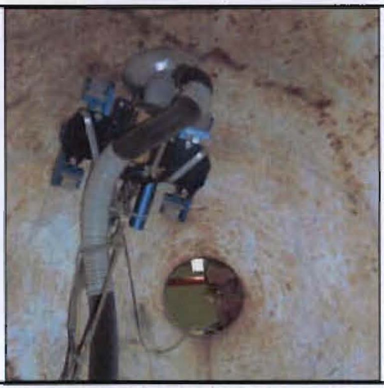

Figure 12. Crawler brushing inside a vessel.

4.2. THE RRC SOLUTION

The most limiting requirement in developing a robotic manipulator system to clean out the spherical containment vessels was that the robot had to be inserted into a 16" Inside Diameter (ID) port. This requirement eliminated a large number of industrial robots that otherwise would have been considered. In developing the system, a total of five commercial robots were reviewed against a number of criteria including payload, robot workspace, mechanical design and maintainability, and controller capability. A thorough review identified a 7 DOF, slightly customized Robotics Research Corporation (RRC) K-1207 manipulator as the best fit for this application (Fig. 13).

Using the RRC robot as a starting point, a number of custom features have been added to the sphere cleaning robotic system. System integration tasks included integrating cameras, developing contamination confinement features, designing a lifting fixture and storage cart, adding safety systems, integrating the various controllers into a single operator workstation, and developing custom end effector tooling.

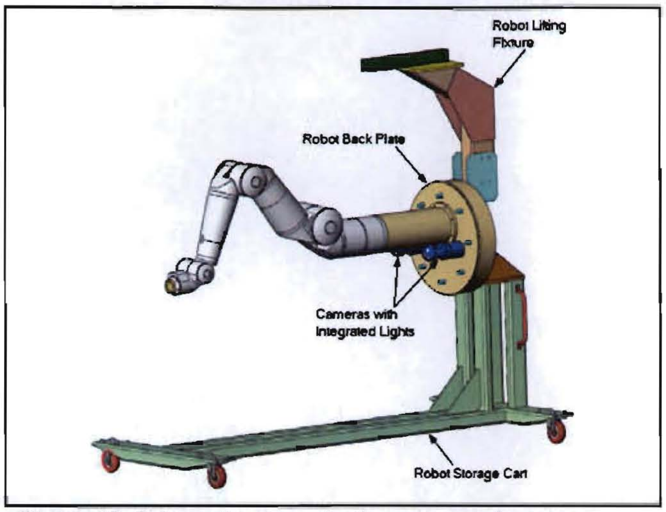

Figure 13. Sphere cleaning robotic system on its storage cart.

The manipulator is operated in both teleoperated and automatic modes. Structured tasks such as tool changes or brushing are done semi-automatically while unstructured tasks like removing large debris are performed using teleoperation. The manipulator is used to remove large debris by passing the debris to a worker at a glovebox workstation attached to the sphere via a 20" ID port. The manipulator is also used to deploy a vacuum cleaner to remove fine debris, to thoroughly brush the inside of the sphere, and to take samples to characterize the radioactivity inside the sphere. Any debris that is too large to remove from the sphere will be size-reduced using the robot. Fig. 14 depicts several cold test applications.

The goal of the cleaning operations is to clean the spheres to the point where they are considered low level waste so that they can be more easily disposed of. To date, the sphere cleaning robotic system is the most complex single manipulator developed for nuclear applications at LANL. More details on this system can be found in Harden [2008].

Figure 14. Cold testing of the sphere cleaning robotic system.

5. FUTURE AUTOMATION DIRECTIONS

The success of the ARIES automation systems has provided a solid technical basis for further development and deployment of automation at LANL (for example, the sphere cleaning robot). By taking small incremental steps, confidence in the technology has been significantly enhanced. Unfortunately, these small incremental steps have also limited the adoption of new and promising technical advances.

In general, the ARIES automation systems lack significant intelligence. There are few if any feedback sensors to enable the system to recognize and self-recover from basic system faults. Some of this is attributable to environmental factors, but architecture decisions also play a role. For instance, the number of wires and thus signals that can be passed from inside the glovebox to outside the glovebox is limited since each wire must pass through a sealed feedthrough connector. Unfortunately, space for those connectors on the surface of the glovebox is limited, and so compromises had to be made between the number of sensors that could be integrated and often signals had to be piggybacked upon other communication pathways.

Maintenance has been and continues to be a concern. Generally, the systems are designed so that operations can be manually executed even in the event of a robot failure. Although such a failure may be unlikely, all of the equipment is designed for manual access. This results in compromises between the automation systems and human operators and produces a system design that is not particularly effective for either user.

The systems reviewed all combine electrical and pneumatic systems in their operation, which can significantly increase the complexity of the resulting automation devices. The trend has been towards self-contained pneumatics, where the entire pneumatic system is housed within the glovebox (although the sphere cleaning robotic system uses house air), and towards electrical tooling and grippers. Unfortunately, technical limitations remain.

5.1. BIO-INSPIRED ROBOTICS

Recently, there has been a renewed interest in bio-inspired robotic solutions for future automation projects. Bio-inspired designs are attractive for two reasons. First, the paradigm that currently exists for glovebox systems to be operatable manually via gloves as well as with automated systems is unlikely to change. In this context, designing automation systems to mimic the kinematic characteristics of a human arm makes considerable sense. These automation systems could be installed in place of a glove and would allow the glovebox systems to be designed for operation from a single perspective and would remove a significant source of containment failure (the gloves) from the glovebox system.

This design paradigm change suggests that the automation systems of the future will resemble the arm used in the Sphere Cleanout project, more than those used in ARIES. But with this added kinematic capability, comes a need for additional on-board intelligence. On-board intelligence, is the second driver in favor of bio-inspired robotics.

While the ARIES systems were designed so as to minimize collision potential, the next generation of robotics will need to accept collisions as possible, but will need to self-recognize collisions before they occur, and execute obstacle avoidance. On-demand system models and real-time recognition of the status to local environment will become necessary. Static environments, such as those currently assumed in ARIES will no longer be the case. Recent work into selective compliance [Rabindran, 2004] would allow soft-collisions, and could even enable robotics to work in proximity to and directly with glovebox workers.

Intelligence might also express itself through enhanced self-diagnostics. Current systems have limited abilities to detect incipient faults and either compensate for those faults to maintain system performance or notify operators that maintenance is needed. This would replace the current maintenance-as-scheduled paradigm with a maintenance-on-demand paradigm. Research into these areas is ongoing [Arvallo, 2000; Hvass, 2004; Turner, 2005, 2006, MacDonald, 2008].

5.2. TECHNOLOGICAL CHALLENGES

Technologically, there are areas which could spur further glovebox automation. The Fanuc LR Mate 100i robots were selected for RIPS in large part because their small size was most appropriate for glovebox automation applications. Most industrial robot models are simply too large to be considered. The same problem limited the number of robots potentially suitable for the sphere cleaning application. Small high-payload arms are highly desirable.

Modular technologies have been considered over the last decade and offer promising advantages in terms of customization and maintenance within glovebox environments. Unfortunately, those advantages come with associated costs, and risk concerns for this new technology. Eventually, a modular solution will be attempted and if modular solutions establish a significant market share, it is likely that the cost disadvantages will be overcome.

Continued development of electrical grippers and tooling will continue to make these the end-effectors of choice for glovebox applications. Notably missing from the market is a suitable all electric tool changer (a few electric tool changers have been developed, but they are not widely available). Suitable current tool changers still require pneumatic connections.

Finally, continued development of intelligent sensors and sensor networks for glovebox environments that will enable enhanced system awareness with local processing capabilities so as to minimize the required connections through the glovebox boundary are also important foundation technology for the development of intelligent automation systems.

6. CONCLUSIONS

The last decade of development and deployment of automation systems at LANL has laid the foundation for further advances. While these systems are not on the cutting edge of automation technology, they reflect the current reality that glovebox application require technologically conservative solutions. The combination of environmental constraints, reliability concerns and the hazardous nature of the work conducted support a conservative and incremental technology adoption policy. Nevertheless, a considerable opportunity for improved nuclear material handling and processing capabilities with reduced ORE exposure is made possible by automation technologies. Further development of key technologies will lead to future generations of automation systems with enhanced intelligence, improved state-awareness, and more flexible bio-inspired robotic designs. While it is unlikely that human workers can be fully replaced, it may become feasible for humans and robots to conduct work as partners in the glovebox lines of the not-so-distant future.

ACKNOWLEDGEMENTS

This paper is approved for release by Los Alamos National Laboratory under LA-UR-09-XXXX. The assistance and support of the ARIES Project staff and the Applied Engineering Technologies Group at Los Alamos National Laboratory, the Robotics Research Group at The University of Texas at Austin and the Division of Engineering at the Colorado School of Mines is greatly appreciated. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of Los Alamos National Laboratory.

REFERENCES

Arvallo, A. (2000). *Condition-Based Maintenance of Actuator Systems Using a Model-Based Approach*, Doctoral Dissertation, Department of Mechanical Engineering, The University of Texas at Austin, Austin, Texas, August 2000.

Brown, W., Rivera, Y., Montoya, E., and Gallant, D. (2008). "The ARIES Robotic Lathe," *Actinide Research Quarterly*, pp. 4-6, LALP-08-004.

Cox, D., Turner, C., Legault, J., and Tesar, D. "Requirements for Small Automation Systems in Glove Box Environments," *ANRC Project 99-11 Report*, The University of Texas at Austin, July 1999.

DOE, (2004). *Stabilization, Packaging and Storage of Plutonium-Bearing Materials*, DOE-STD-3013-2004, U.S. Department of Energy, Washington, DC.

Foster, C., Turner, C., Cox, D., Tesar, D., and Pittman, P. (2001). "Computer Model and Simulation of a Glovebox Process," *American Nuclear Society Proceedings of the 9^{th} Topical Meeting on Robotics and Remote Systems*, Seattle, Washington, March 2001, LA-UR-01-0314.

Heywood, A. and Armantrout, G. (1990). "Robotic Requirements for Plutonium Handling Automation," *IEEE Transactions on Nuclear Science*, June 1990, **37**:3, pp. 1452-55.

Harden, T. and Pittman, P., "Development of a Robotic System to Clean Out Spherical Dynamic Experiment Containment Vessels", *Proceedings of the ANS 12th International Topical Meeting on Robotics and Remote Systems*, March 2008.

Hintenlang, D., Tulenko, Wheeler, R. and Roy, T. (1990). "Environmental Hardening of Robots for Nuclear Maintenance and Surveillance Tasks," *Transactions of the American Nuclear Society*, **61**, pp. 410-11.

Hvass, P. (2004). *Condition Based Maintenance for Intelligent Electromechanical Actuators,* Masters Thesis, Department of Mechanical Engineering, The University of Texas at Austin, Austin, Texas, August 2004.

LANL, (2008). *Radiological Worker II Training Manual*, LANL, Los Alamos, New Mexico, LA-UR-07-2308, p. 31.

Lumina, R., Starr, G., Wood, J., Jones, B., Shohet, I. and Ledman, E. (1997). "An Approach to Minimize Robotics System Development and Integration Time," *Proceedings of the 1997 IEEE International Conference on Robotics and Automation*, April 20-25, 19997, **4**, pp. 3220-25.

MacDonald, J., Turner, C., Nekimken, H., Evans, M., and Moya, J. (2008). "An Introduction to Vitals," *2008 ASME Design Engineering Technical Conferences*, CIE-49859, Brooklyn, New York, August 2008, LA-UR-08-0636.

McKee, S. (2008). "ARIES at 10," *Actinide Research Quarterly*, pp. 1-6, LALP-08-004.

McQueen, M., Ashok, P., Turner, C., Cox, D., Hollen, R., and Pittman, P. (2001). "Use of Simulation to Examine Operational Scenarios in a Lathe Glovebox for the Processing of Nuclear Materials," *Proceedings of the American Glovebox Society 2001 Conference and Exposition*, July 2001, LA-UR-01-3701.

Pittman, P., Harden, T., "Sphere Cleanout Robot Requirements and RFI," Los Alamos National Laboratory, LA-UR: 02-7848 (2002).

Rabindran, D. (2004). *Preliminary Studies on Force/Motion Control of Intelligent Mechanical Systems*, Masters Thesis, Department of Mechanical Engineering, The University of Texas at Austin, May 2004.

Turner, C., Legault, J., and Cox, D. (1999). "Specifications for Small Automation Systems in Glove Box Environments," *Report to the Amarillo National Resource Center for Plutonium*, The University of Texas at Austin, October 1999.

Turner, C., Legault, J., Cox, D., and Tesar, D. (2000). "Configuration Management for Modular Flexible Small Automation Systems: A Case Study," *2000 ASME Design Engineering Technical Conferences*, MECH-14122, Baltimore, Maryland, September 2000.

Turner, C. (2005). *Hyperdimensional Performance Models for Engineering Design,* Ph.D. Dissertation, Department of Mechanical Engineering, The University of Texas at Austin, Austin, Texas, December 2005.

Turner, C., Ajetunmobi, A. and Crawford, R. (2006). *"Fault Detection with NURBs-Based Metamodels," 2006 ASME Design Engineering Technical Conferences*, CIE-99637, Philadelphia, Pennsylvania, September 2006, LA-UR-06-3542.

Turner, C. and Lloyd, J. (2008). "Automating ARIES," *Actinide Research Quarterly*, pp. 32-5, LALP-08-004.

Wenz, T., Herrera, G., and Guillen, B. (2008). "ARIES Nondestructive Assay Instrumentation," *Actinide Research Quarterly*, pp. 28-31, LALP-08-004.