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RESEARCH ON THE USE OF ROBOTICS IN HAZARDOUS ENVIRONMENTS AT SANDIA NATIONAL LABORATORIES*

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ABSTRACT

Many hazardous material handling needs exist in remote unstructured environments. Currently these operations are accomplished using personnel in direct contact with the hazards. A safe and cost effective alternative to this approach is the use of intelligent robotic systems for safe handling, packaging, transport, and even excavation of hazardous materials. The Intelligent Systems and Robotics Center of Sandia National Laboratories has developed and deployed robotic technologies for use in hazardous environments, three of which have been deployed in DOE production facilities for handling of special nuclear materials. Other systems are currently under development for packaging special nuclear materials. This paper presents an overview of the research activities, including five delivered systems, at Sandia National Laboratories on the use of robotics in hazardous environments.

INTRODUCTION

The Intelligent Systems and Robotics Center (ISRC) at Sandia National Laboratories (SNL) has always viewed the use of robotics in hazardous environments as one of the most important areas for research and development. Pat Eicker, Director of the ISRC, argues that "because of a unique confluence of events, hazardous applications will provide the impetus necessary to start achieving the promise of intelligent machines"[1]. This was in response to an observed trend that the research and application of robotics and intelligent machine technologies has decreased quite dramatically in the past few years. Eicker further observed that the federal government, specifically the Department of Energy (DOE), possesses a range of hazardous applications that has "motivated initiation of the critically interrelated processes of research, development, and application of the technologies" that are required for fulfilling the needs of the DOE. Furthermore, the developed technology base for solving problems in these hazardous environments is found to be useful in a broad range of other applications.

Based on direct feedback from the user community of hazardous applications where intelligent systems could have an impact, their needs can be divided into the following four categories [1]:

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DISCLAIMER

1. Production and Dismantlement Operations Involving Hazardous Materials – Technologies in this category include demilitarization of chemical and nuclear weapons, small lot production of weapons, agile manufacturing, and "instantly responsive" change of production rates.

2. Characterization and Remediation of Environmentally Contaminated Sites – This category includes characterization and remediation of waste storage tanks, facility deactivation, size and volume reduction, separation of materials, and packaging and storage.

3. Automation of Hazardous Sample Handling, Preparation, and Analysis – This category primarily addresses analyses of hazardous samples which are either handled remotely with manipulators or manually through glove box ports. Sometimes, the number of samples that requires preparation and analyses is very large and traditional remote handling and glove box operations do not provide the required throughput.

4. Hazardous Materials Facility Operations – These are facilities where inactive or waste materials are stored and await final disposition. The materials are hazardous and thus require remote handling. Applications in this category are highly varied. For example, drums are received, inspected, unpacked, the contents sorted, repackaged, and then sent to storage. This might be done remotely, and could involve transportation of the hazardous packages to a prepared storage facility such as the Waste Isolation Pilot Plant (WIPP).

This paper describes five systems that have been delivered to address some of the needs as described in the above four categories. In addition, a summary of the simulation tools used to help develop technologies used in hazardous environments will be given.

RETRVIR

Many hazardous material handling needs exist in remote unstructured environments. Currently, these operations are accomplished using personnel in direct contact with the hazards. A safe and cost-effective alternative to this approach is the use of intelligent robotic systems for the excavation, handling, and transport of these hazardous materials. The mobile robot, RETRVIR, or REmote TeleRobotic Vehicle for Intelligent Remediation [2], incorporates recent developments in the integration of sensors, advanced computing environments, and graphical user interfaces. This robotic system successfully integrates computer-controlled manipulation and mobility to deliver these needed robotic capabilities in the field.

The complete mobile manipulation system consists of a remote manipulation and excavation robot (RETRVIR), incorporating a remotely piloted vehicle and hydraulic manipulator, and a mobile control center which houses the operator control station and a transportation/work area for the robot. RETRVIR, shown in Figure 1, consists of a Honda Pilot™ off-road vehicle modified for remote operations. The on-board control computing systems and communication modules were placed at the original location of the driver to provide a weight distribution similar to that of the standard unmodified vehicle. The control computers use sensory information and models of vehicle performance to map and turn the remote driver commands into control inputs for the vehicle control actuators on the gear-shift, throttle, brake, and steering mechanism. Other equipment includes cameras for live video, a global positioning system, and various sensors to monitor on-board system status and external parameters, such as nearby obstacles. Electrical power for the added equipment is produced by a generator mounted on the vehicle. The seven-foot robotic arm, mounted on the front of the vehicle, is a hydraulic manipulator with six degrees of freedom. It is capable of lifting up to 650 pounds. As shown in Figure 1, the hydraulic manipulator is mounted on the front end of the vehicle to provide maximum forward reach. The vehicle's rear mounted engine counter balances both the arm's weight (180 lb.) and any anticipated payloads. An on-board hydraulic power unit produces hydraulic power for the manipulator.

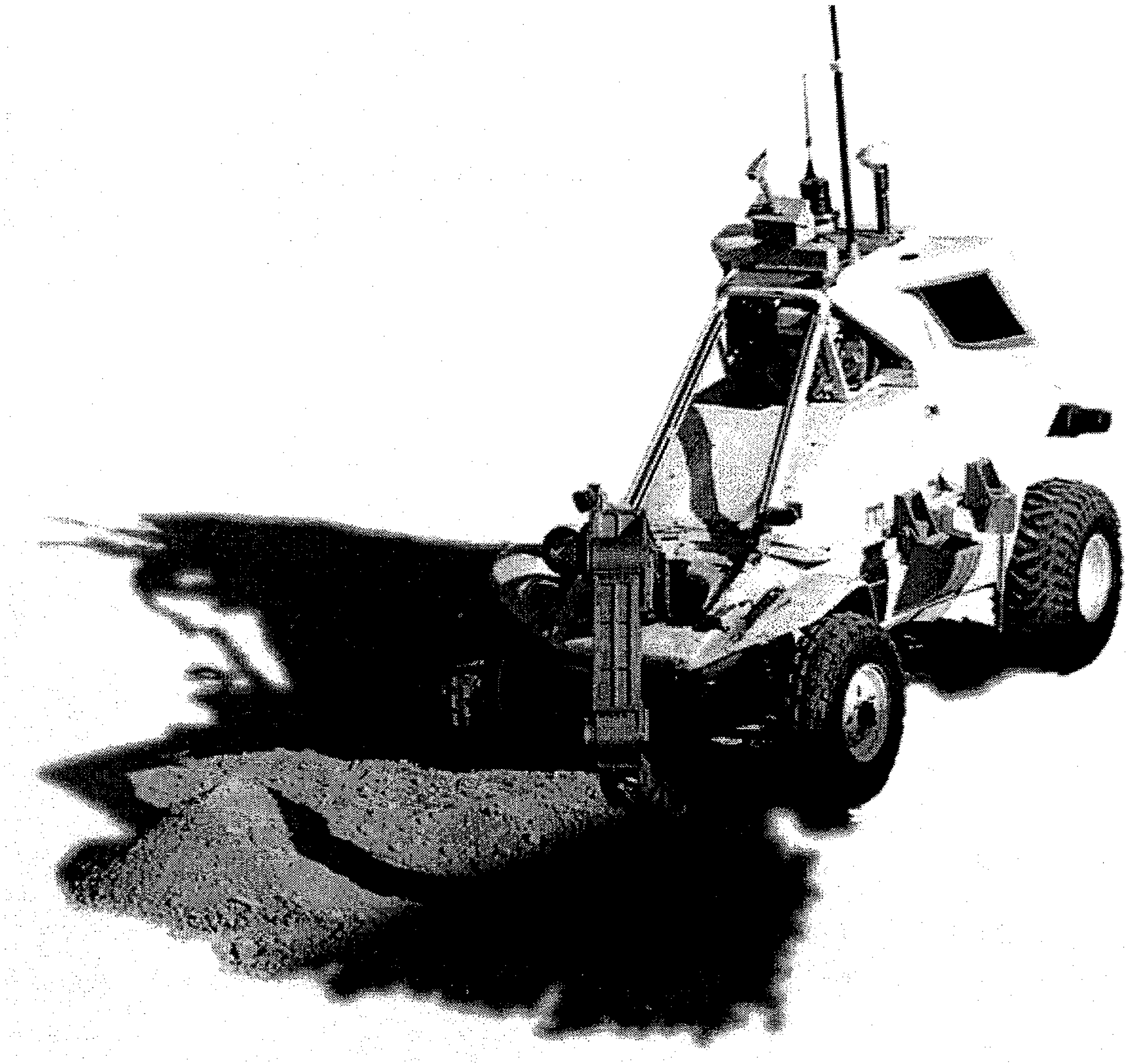


Figure 1: RETRVIR Performing Excavation with the Hydraulic Manipulator.

The RETRVIR system has been deployed on several occasions. The first was to carry out waste retrieval operations in an actual buried waste site. The hazards associated with the buried chemical and explosive materials in this landfill make clean up a high priority, yet prevent personnel from entering and removing waste. Combined automated and remote manual operations allowed RETRVIR to quickly and safely remove soil, automatically approach unknown objects, and then grasp and remove objects from the uneven terrain of the waste pit. The remote camera systems and high-dexterity computer controlled robot arm allowed the retrieved objects to be visually inspected and carefully placed in plastic bags. The unknown waste was then carried by RETRIVR to the entrance of the pit for pick up and laboratory analysis by technicians. Retrieval operations were continued for two days, and site remediation technologists expressed delight in the ability of the system to respond quickly to a critical need by performing operations not possible using conventional approaches.

The second deployment was at the Jefferson Proving Grounds in Madison, Indiana for one week, to participate in field tests supported by the Navy Explosive Ordnance Disposal Technical Center. The purpose of these tests was to determine the current capabilities in the areas of sensing and mechanical clearance of buried munitions. This test proved to be very valuable for the RETRVIR team: it allowed the system to be tested under real world conditions and for the system's strengths and weakness to be evaluated. In the third deployment, RETRVIR carried out waste retrieval operations in a bomb disposal pit used to store sub-munitions (bomblets) at the DOE's Tonopah Test Range. The pit, which is approximately twenty feet long and ten feet wide, contained over two thousand bomblets as well as many remnants from other large ordnance such as tail cones and fins. RETRVIR's versatility allowed the robot to enter the pit and retrieve over a thousand individual bomblets, as well as excavate and remove many pieces of scrap metal. Control of RETRVIR was accomplished from the system's control center stationed three thousand feet away from the waste pit. Once the bomblets were removed, they were deposited at a processing pad where shaped charges were attached to render them inert and safe.

ACCIDENT RESPONSE MOBILE MANIPULATOR SYSTEM

While the RETRVIR is a single manipulator system, the ARMMS (shown in Figure 3) is equipped with two hydraulic manipulators and is capable of performing coordinated manipulation with both arms simultaneously. The Accident Response Mobile Manipulator System (ARMMS) was developed for worldwide accident response use by the DOE's Accident Response Group. In the event of an accident (including nuclear accidents), the ARMMS allows an operator to remotely access an accident site and manipulate items for thorough investigation. The ARMMS system is designed with both vehicular and robotic characteristics that supports salvage and recovery operations that previously would have put people in harm's way. Using a military High Mobility Multi-purpose Wheeled Vehicle (HMMWV, pronounced Humvee) as the platform, ARMMS was developed with the full range of capabilities necessary to provide comprehensive accident response. It can be deployed in a teleoperational capacity using a single fiber optic cable that provides ARMMS a range of up to four kilometers, or remotely with a radio frequency (RF) communication link. In the event of damage to the fiber optic cable, the RF system automatically activates for vehicle movement or retrieval. The ARMMS can also be driven like a regular HMMWV and carries an equipment shelter that can be deployed as a command post for teleoperated activities. Besides providing teleoperational capabilities, the fiber optic cable communication system interfaces with a Portable Integrated Video System (PIVS) for surveillance capabilities. Both the "driving" camera and a camera mounted on a 20 foot telescoping mast are equipped with zoom lenses and positioners for survey of the surrounding terrain. An on-board mapping and sensor package detects and locates radioactive debris and hazardous gases.

The ARMMS provides the following features:

- Highly mobile, four wheel drive vehicle
- Two Schilling titanium manipulator arms
- Lifting capability 250 pounds at full extension of 78 inches

- Computer-controlled manipulator arm operation
- Global Positioning System (GPS) with one-meter accuracy
- Navigation mapping system
- Hazardous gas and radiation sensor package
- Five on-board video cameras
- All-weather command/control shelter with stand-alone power source
- Fiber-optic cable deployment system
- Back-up RF control system
- Communications mast telescoping to 20 ft.

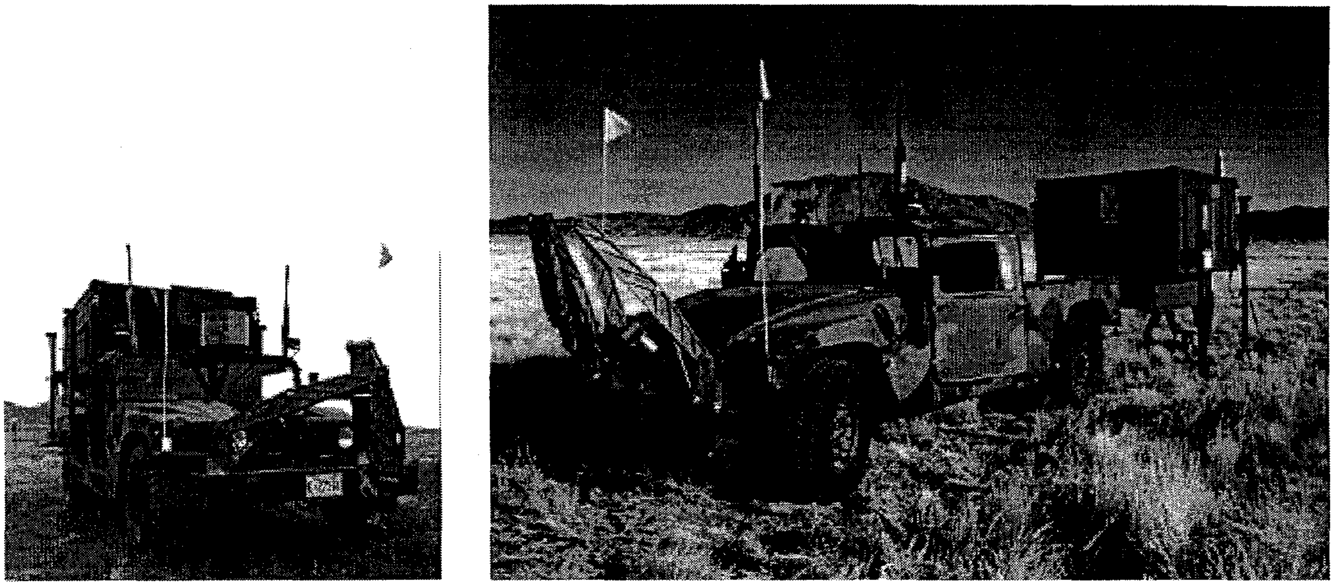


Figure 2: ARMMS in Transition; Deployed with the Control Module Behind the Vehicle.

The ARMMS system is designed to allow the operator to manually drive the system to a safe distance from the accident site, deploy the control module, then remotely control the vehicle to the accident site using the vehicular control console in the control module. After parking the vehicle at the accident site, the operator uses the on-board cameras to assess the status of the accident scene. In addition, the two hydraulic manipulators can be used to further investigate situations where direct camera views are not possible.

The Sandia developed Sequential Modular Architecture for Robotics and Teleoperation (SMART) technology was recently added to the ARMMS. SMART allows coordinated control of both manipulators simultaneously while performing a single task. This technology enables the operator to control the path of the end-effector directly. This makes the system extremely user friendly and thus reduces operator training time by a great deal.

Automated Gas Generator Disassembly

The ISRC and Explosive Subsystems and Materials Department at Sandia National Laboratories have worked closely with Mason and Hanger staff at the DOE Pantex Plant to develop a robotic workcell, which automatically disassembles explosive gas generators from nuclear weapons that are being, demilitarized [3]. Manual disassembly is potentially hazardous because of stabilizer depletion in the propellant. Burning the units was considered, but this process has some potential hazard to operators and the resulting waste stream is lead-contaminated. Automated disassembly was chosen to ensure operator safety while yielding uncontaminated products, most of which could be recycled. The required process steps are: remove the threaded locking ring, remove the closure disc, pour out the propellant, dislodge any remaining propellant, remove the threaded igniter, and place the igniter on a pallet. Required operations include aligning spanner and socket wrenches with components, unscrewing threaded components, pouring propellant, and handling sensitive igniters.

Figure 3 shows the Automated Gas Generator Disassembly (AGGDIS) robotic system. The system consists of a workcell that uses simple fixturing where appropriate. Force sensing, force-controlled motion, and computer vision are used to accommodate remaining variations in the process. The system uses force control to ensure that the force and mechanical shock applied to work pieces are minimal. The robot performs most of the handling processes, but cannot deliver the torque required for removal of threaded sub-components. A powered socket was developed to provide up to 200 ft-lb of torque. The robot manipulates specialized wrenches in order to incorporate parallel jaw and vacuum grippers, so as to grasp parts as they are unscrewed.

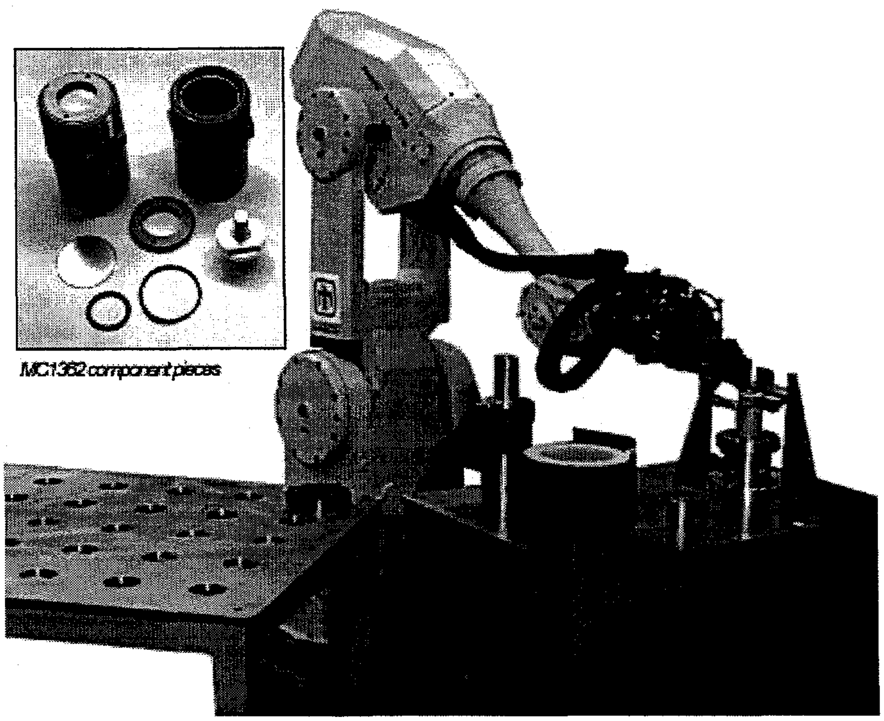
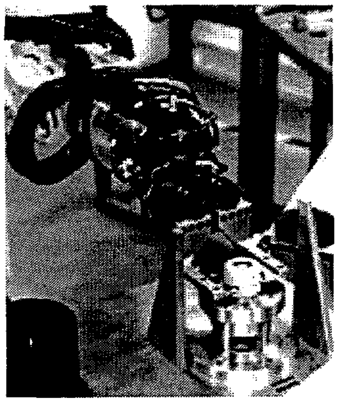
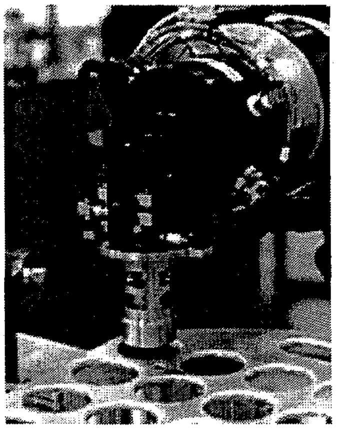


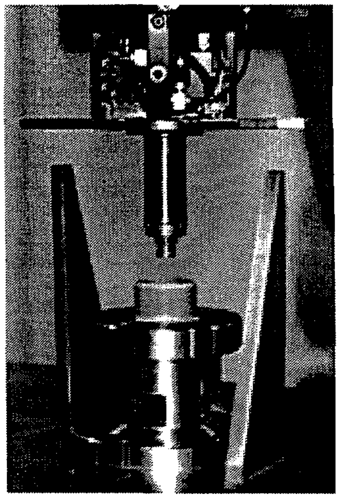
Figure 3: Automated Gas Generator Disassembly (AGGDIS) Robotic System.



Gas generator placement into the powered socket



Igniter removal from gas generator case



Igniter placement into pallet

Figure 3: Automated Gas Generator Disassembly (AGGDIS) Robotic System (Cont.).

Motion of the robot and powered socket are closely synchronized by a Programmable Logic Controller in communication with the robot controller. The operator controls the system with a graphical, push-button interface running under Windows on a PC. The design allows control from a remote location, eliminating personnel hazards.

The workcell is currently operational at the Pantex Plant, where it has completed demilitarizing the stockpile of earlier version gas generators, and is currently demilitarizing a newer generation.

The experience gained on the AGGDIS system provided an opportunity for SNL to further expand the application of this technology to solve problems associated with conventional munitions. There are hundreds of thousands of munitions remaining from as far back as World War II that need remediation and disposition. Similar to the gas generators, they contain unstable explosive materials that require dismantlement. Keeping the operators from hands-on performance of these functions reduces potential injuries from an accidental explosion during dismantlement. At the ISRC, another workcell was developed to determine the technologies required for disassembling fixed-round munitions. Fixed-round munitions range from 20mm diameter to 105mm diameter rounds, all of which have a cartridge case, percussion primer, propellant, and a projectile. This system was developed for the McAlester Army Ammunition Plant and will be used for dismantlement of 40mm rounds.

WALS

The Weigh and Leak Check System (WALS), as shown in Figure 4, was developed for the Pantex Plant to handle surveillance and confirmation measurements on "pits," which are the radioactive cores of nuclear weapons [3]. WALS unpacks and repacks a variety of containers and performs weighing and leak checking of stockpile pits. The operation ia as follows: WALS removes a pit from a storage container. It then takes the pit to several weigh and leak check operations, records the results of these operations, repacks the pit into an appropriate container, and returns it to storage. The system can handle any of seven different sized pits in any order. (Packing and unpacking is a tedious job that exposes workers to radiation.) With WALS, the operators are in an adjacent room and operate the system by computer, using a graphical user interface which is a computer-generated "picture" of the actual machinery. If any unexpected pit configurations are encountered, they can perform the process manually. The system was delivered to Pantex in the spring of 1997.

This system deviates from typical industrial use of robots in that the WALS robot performs numerous operations at many stations in a single workcell with several specialized grippers and tooling stations. This is in contrast to typical industrial applications where, for example, a robot performs a number of machining operations on the assembly line before the part moves to another robot to continue with different machining operations.

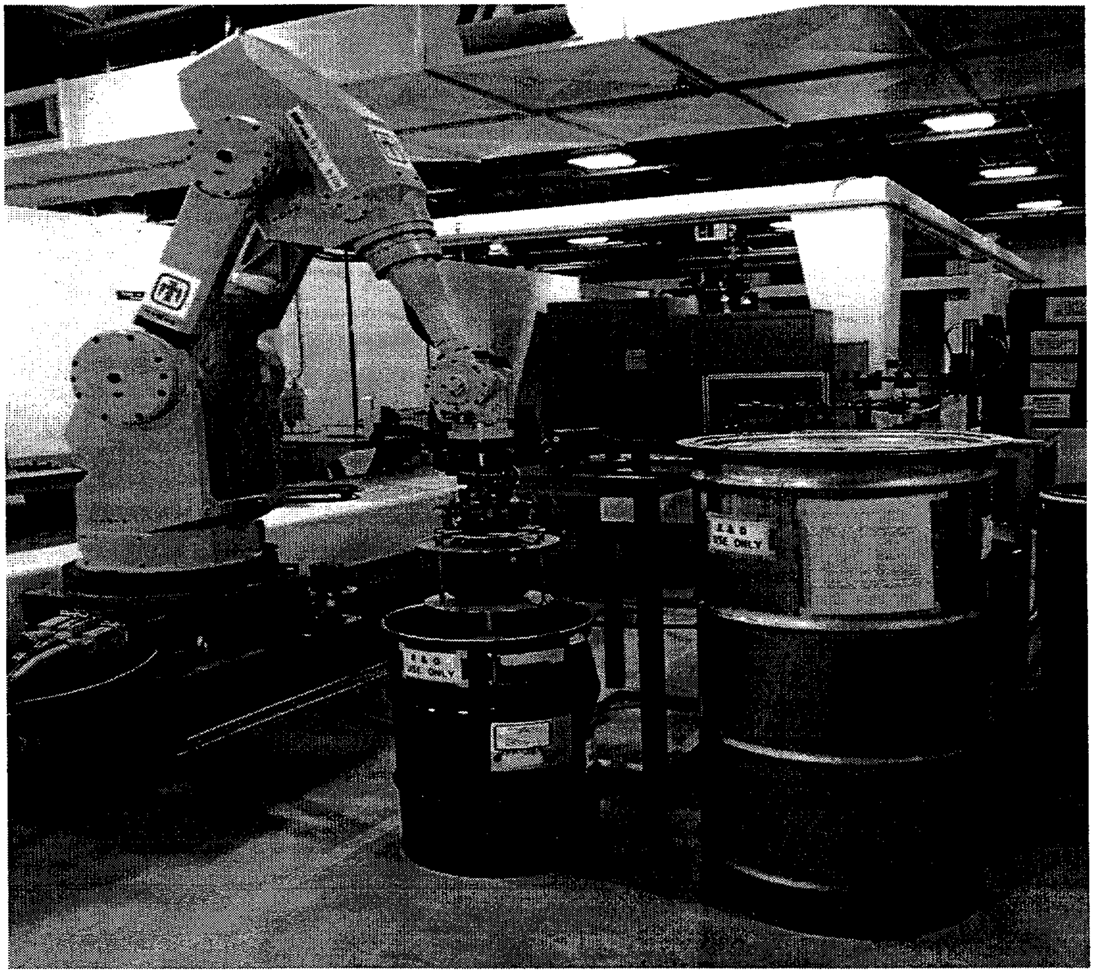


Figure 4: Weigh and Leak Checking System (WALS).

STAGE RIGHT

Stage Right uses an automated guided vehicle (AGV) to remotely handle and monitor drums containing plutonium pits removed from nuclear weapons [3]. Technicians operate the system from a nearby trailer and thus significantly reduce their exposure to radiation. Sandia worked closely with Hyster Corp., a material handling company, to develop this system. Because of demilitarization, storage density requirements for pits almost doubled following the end of the Cold War. The denser storage arrays creates higher radiation levels for routine operation using human operators. Stage Right successfully removes human operators from routine radiation exposure that results from the higher storage density. Because of Stage Right, the pit storage at Pantex is roughly twice the previous capacity. Sandia has subsequently added a number of sensors and operator aids, including a graphical user interface. Stage Right became operational in June 1996, and is moving pits weekly.

The Stage Right system allows an unmanned automated guided vehicle to carry the drums into and out of the large magazines rather than people driving forklifts. For surveillance and inventory operations, AGVs equipped with sensors are also able to perform surveillance and inventory procedures. These functions are performed by an operator sitting in a small trailer on the road next to the magazine. The operator uses a computer interface that graphically presents the layout of the magazine storage array. The operator performs the appropriate inventory operations from the computer interface, where the operator will not be exposed to excessive radiation levels.

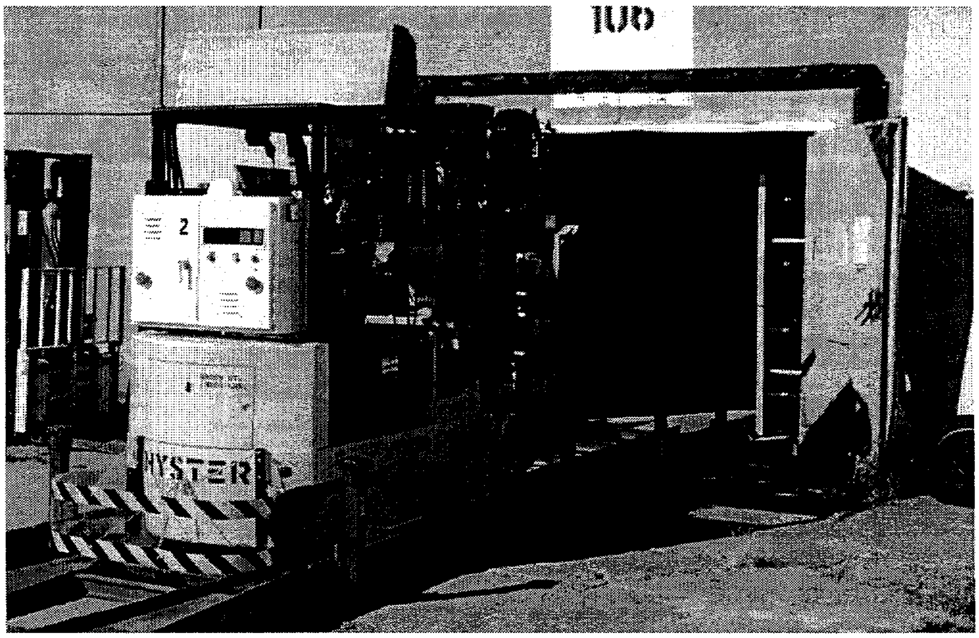


Figure 5: Stage Right Entering a Magazine.

DESIGN, SIMULATION, AND ANALYSIS TOOLS

Development of robotic technologies for use in hazardous environments requires proper design, simulation, and analysis tools. The ISRC uses many commercial and in-house simulation tools to address system development needs in design, visualization, model-based control, and training. Where simulation is not feasible or requires further validation, the ISRC uses its prototyping facilities to provide experimental data to support development. Some ISRC in-house extensions to commercial simulation software have been driven by teleoperation needs. Other ongoing work seeks to bring design into the loop more tightly by combining automated planning with process-feasibility analysis and blending simulation technology with CAD. Commercial simulation tools in daily use in the ISRC include:

- robot workcell-level simulators, such as Deneb's IGRIP and TELEGRIP, Silma's Cimstation, and Cimetrix's Cimulation;
- human/machine interaction simulations, such as ERGO Man, and Transom Jack; and

- discrete-event simulators, such as ARENA, for factory system simulation.

To address needs not met elsewhere, the ISRC has developed several modeling, simulation, visualization, operator interface, controls, and CAE tools. Some of these extend commercial products, while others are full in-house system development or integration environments. Sandia has also developed several other software packages that provide fundamental capabilities in simulation and automated programming and planning. Tools and systems include:

- Sancho, a Graphical Programming system and Virtual Collaborative Environment;
- REMS, which adds radiation dosimetry to IGRIP simulations; and
- System Composer, an environment that assists in defining manufacturing system requirements and maps them to a component-level system definition.
- SMART, a modular control technology that is used both for haptic interface development and for piecewise refinement of control systems;
- Archimedes, an automated assembly planner;
- SANDROS, a motion-planner whose performance smoothly bridges the gap between interactive and off-line motion-planning;
- Umbra, an object-oriented, extensible simulator kernel;
- the C-Space Toolkit, a library providing fast distance and interference computations; and
- Holdfast, which automatically designs fixtures for a given part, process, and modular fixture kit.

CONCLUSION

Five robotic systems designed for use in hazardous environments were presented in this paper. Although each of the systems uses similar equipment, the tasks performed vary greatly, yet all are designed to reduce hazards to workers at the plant or in the field. Since the early 1990s, the Department of Energy has sought to ensure that advanced robotics technology is being implemented in the nuclear weapon production complex. The objective is to reduce hazards to workers in operations involving radioactive materials or explosives. In addition, the paper summarized the design, simulation, and analysis tools that are used at Sandia for development of robotic systems for use in hazardous environments.

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