# A Modular Approach to Robotic Automation of DOE Applications

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## Abstract

The Department of Energy (DOE) faces many unique challenges in the automation of operations within each of Environmental Management's focus areas. ARM Automation has developed a modular architecture that addresses many of the DOE's automation requirements. This paper outlines technical progress of the first system being built, under Contract # DE-AC26-98FT40371, using this modular approach; a robotic manipulator tailored to the needs of glove box operations constructed from two sizes of intelligent actuator modules, quick-connections, links and an open architecture system controller. The proposed test plan for quantifying this system as it applies to the DOE is then presented. This is followed by a synopsis of the overall applicability of modular robotic technology to DOE EM applications. Finally, ARM Automation is working under an SBIR award titled "Modular Robotics for Delivering On-Site Contamination Sensors and Mapping Systems to Difficult-to-Access Locations" to refine and apply this technology to an EM application. A description is given of ARM's goal under the SBIR of exploring the application of the modular approach to another DOE application: presenting a sensor into a contaminated area that is in need of characterization.

## Introduction

The Department of Energy (DOE) faces unique technical and operational challenges to automate operations in each of its Environmental Management focus areas. A survey was conducted by [Geisinger] which examined the robotic requirements of 4 areas in some detail; Decontamination & Dismantlement (D&D), Mixed Waste Operations (MWO), Tanks and Automated Plutonium Processing. This investigation into these and other areas showed that the range of applications proposed for robotic automation vary widely in needs such as degrees of freedom, kinematics, payloads, reach and force control. The study also revealed that these operations share characteristics such as confined spaces, extremely harsh environmental conditions and the need for simple field serviceability and often portability. Combined, these factors preclude the practicable use of most industrial robots, leaving problem holders faced with the development of custom robotic solutions.

The development of a custom robotic system using conventional technology requires expertise in specification and integration of low-level machine components (motors, gears, sensors, etc.), the design of custom hardware and the integration of system control software and electronics. In addition, this "from scratch" development process requires additional assembly, debugging and documentation. This development process can take months to years and consumes the efforts of valuable personnel and resources. Only once this development has been completed can the automation be integrated into the process for which it was designed. Additionally, due to the proprietary nature of such development, complete documentation of such "in house" systems are difficult or impossible to maintain once the original project engineers have moved on, leaving behind legacy systems which are difficult to operate or maintain.

# Objective

The present modular robotic system was proposed to the National Energy Technology Laboratory in 1997 as a pre-engineered robotic tool kit for addressing the unique and challenging automation applications within EM operations. This system was developed as an extension of ARM Automation's core product and prior experience in portable robotics and modular automation. During the scope of this project, two sizes of actuator module, interconnecting links and a system controller were redesigned to enhance performance and to better satisfy the requirements of EM operations. This project culminates in the production of two demonstration manipulators suited to the performance of tasks within the confines and design constraints of a actinide handling glovebox.

In redesigning this modular system, the needs and requirements of many EM focus areas were taken into consideration. However, given the final scope and funding of the project, it was necessary to select one area of operations for the purpose of manipulator configuration and demonstration. As a design case, glovebox operations, particularly those involved in the handling of Plutonium laden materials, were selected because of the size of the manipulators required, versus some other D&D tasks, as well as the pressing need for a workable solution in this arena.

**The Challenge of Glovebox Automation**

The geometry of gloveboxes, used in the production, handling and disposal of nuclear materials, can vary as significantly as the operations which they enclose. The majority of these enclosures are stainless steel vessels, sealed and shielded typically with material access ports on the ends and glove ports and windows along one or more sides (see Figure 1). These glove ports (typically 8½" in diameter) allow workers to reach into the enclosure and manipulate materials by hand. Unfortunately, the proximity to materials often exposes workers to significant levels of radiation and provides opportunities for direct exposure in the event of a seal breech or other mishap. Additionally, reaching through fixed portals and wearing heavy gloves also quickly leads to worker fatigue and limits productivity. Combined, these factors lead to the need for automation in glovebox operations.

**Figure 1: "Double Wide" Glovebox**

Unfortunately, implementing automation within the confines of an environmentally sealed container has proven far from trivial. In some respects, the automated handling of actinide-laden materials is similar to many industrial tasks, but the unique environment and material create the following set of challenges [McKee] :

I. Plutonium contaminated environment
   A. Low to moderate levels of ionizing radiation
   B. Highly abrasive
   C. Corrosive
   D. Pyrophoric

E. Plutonium disperses and permeates readily
F. Reaction and behavior with equipment is not well understood

II. Other challenges to glovebox automation
A. Highly confined operating space
B. Existing gloveboxes may not be readily altered or modified
C. Complex maintenance and repair are difficult or impossible through gloves
D. Failed equipment may not be removed easily or, in some cases, at all
E. Workspace often requires unconventional work envelopes

Given the value of glovebox floor space, equipment and materials are often more crowded in arrangement than behooves robotic automation. A minimization of robot footprint and "elbow room" is absolutely critical. At the same time, the reach or workspace required of a glovebox automation robot may be considerable given the potentially high span to height ratios of these vessels. Unfortunately, these criteria, compactness and large work envelope to size ratios, are not typically found in the design of robotics for industrial use. In addition to avoiding contact with process equipment within the box, it is imperative that any motion devices in the container not contact the walls, windows or ports of the glovebox, lest a potentially disastrous collision occur. To ensure that collisions do not occur, robot kinematics may be designed such that the arm cannot reach the walls of the box, or hard limits may be used to prevent any joint combination from contacting the wall. Both options can severely limit the dexterity and working envelope of a system. Another option would utilize collision avoidance software to prevent accidents, however, at present, there are no known robot vendors offering this level of technology.

Connecting with automation inside a glovebox presents its own challenges. Conventional electric robotics and automation devices utilize a large number of wires (15-20) per axis to carry control signals, power and other information to and from each servo axis. With an umbilical for several axes (typically 6) entering into a glovebox, connectors and wires can quickly stack up, increasing the most common points of failure in automation equipment while virtually eliminating the possibility of their repair. Hydraulic manipulators, on the other hand, are unacceptable in most cases because of the added hazards associated with leaking hydraulic fluid both inside of and that leaving the otherwise sealed confines of the glovebox.

In the event of any component failure, if a broken piece of equipment cannot be "bagged-out" through a glove port it must remain in the box. Such broken equipment obstructs further operations. If it renders the entire glovebox unusable, a significant volume of waste is generated and an expensive system must be disposed of and replaced. Additionally, when materials must be disposed of following any irreversible contamination, it is most desirable that they fit into standardized containers such as the 55-gallon drum sized containers suitable to the WIPP.

Together, these constraints and criteria for glovebox robotics and automation create a narrow window of opportunity for design. Any proposed solution must circumvent these limitations and do so while providing complete functionality and reliability expected in today's state of the art robotics systems.

## Approach

In order to address this need for quick and powerful robotic solutions, ARM Automation has developed a system of modular "building blocks" which allow users to quickly design and build custom robotic systems such as transfer machines, positioning stages and manipulators suitable to a wide variety of applications. These building blocks are assembled into systems through the use of quick-connect electro-mechanical interfaces and leverage a unified distributed control technology that greatly reduces the wiring requirements of a robotic system. Through the use of this “toolbox” of modules, it is then possible to circumvent many of the limitations imposed by off-the-shelf robotics, while avoiding the time, cost and risk of building custom systems from scratch to address DOE-EM needs. Within the scope of this project, ARM has developed 2 module sizes and interconnecting links suitable for creating small to mid-scale robotic manipulators.

## Description of Modular Manipulator Technology

Each module in this family of modular “building blocks” is based upon a core technology called the DISC™. DISC™ stands for **D**istributed **I**ntelligent **S**ervo **C**ontrol. Each DISC™ device is a miniature control and communications node which can be linked with other DISC™ devices to create a distributed control network of motion devices and sensors. DISC™ devices communicate over an industrial communications protocol called SERCOS, which is specifically designed for high-speed communications between motion control devices. The digital, distributed control along with this digital communications protocol provides noise immunity, real-time communications and, most importantly, reduces the scores of control wiring 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 required by conventional approaches.

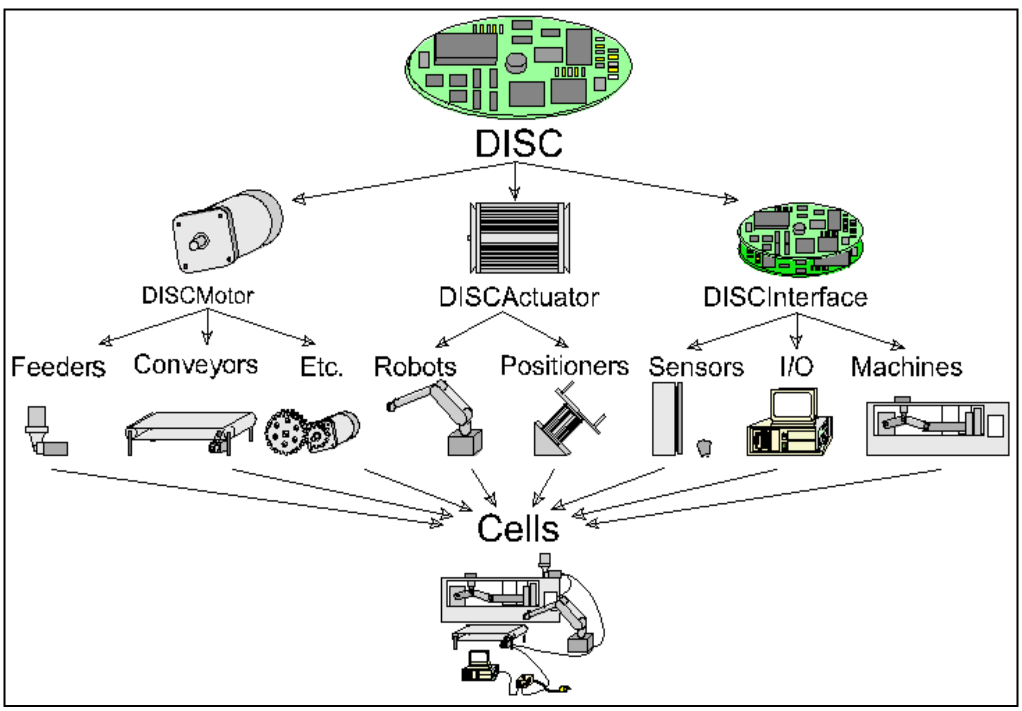



**Figure 2: Family Tree of DISC™ Enabled Devices**

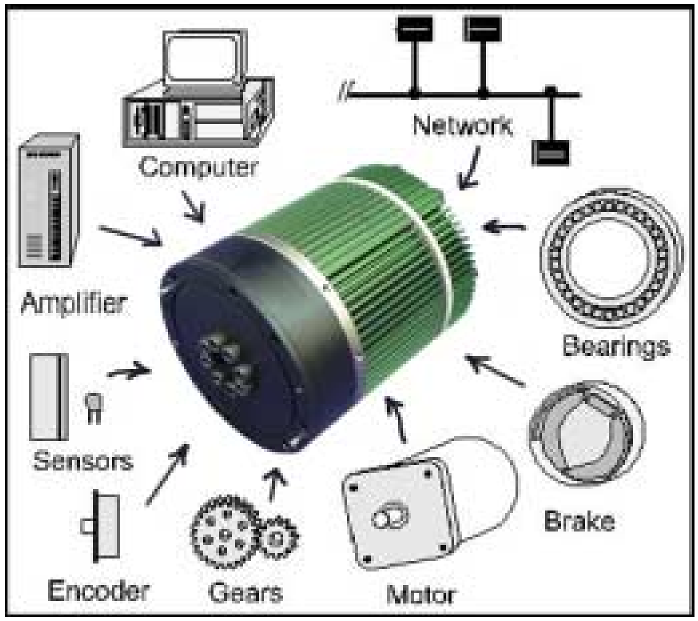



**Figure 3 ARM Actuator Module**

As shown in Figure 2, DISC™ devices can be used to enable various devices used in industrial automation, ranging from robotic actuators to remote data acquisition. In order to construct a series of robotic manipulators, two sizes of actuator module (the ARM20 and ARM32) were designed during this project. Each actuator module incorporates a DISC™ amplifier along with a high performance brushless DC motor, position/torque sensors, gearing, structural bearings, fail-safe brake, and other components to form a pre-engineered package. This pre-engineering reduces the integrator's interface to the actuator specifications shown in Table 1. 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.

By utilizing these actuator modules and interconnecting links, robotic arms can be assembled in a variety of kinematic (geometric) configurations by selection of appropriate actuators, links and yokes.(see Figure 4) Each link module is simply a tubular or linear extension of an actuator module, while yoke adapters convert roll modules into pitch joints. 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

| | **ARM20** | **ARM32** |
|---|---|---|
| ***Performance:*** | | |
| • Range of Motion | ± 340° (or continuous*) | ± 340° (or continuous*) |
| • Peak Speed | 30 RPM | 35 RPM |
| • Peak Torque | 82 N×m (60 ft×lb) | 333 N×m (245 ft×lb) |
| • Continuous Torque | 40 N×m (30 ft×lb) | 137 N×m (101 ft×lb) |
| • Bearing Load Capacity | 3330 N (740 lb) | 7550 N (1716 lb) |
| • Bearing Overturning Load | 333 N×m (245 ft×lb) | 755 N×m (555 ft×lb) |
| ***Physical:*** | | |
| • Length | 128 mm (5.0 in) | 151 mm (6.3 in) |
| • Diameter | 97 mm (3.8 in) | 129 mm (5.7 in) |
| • Mass | 2.3 kg (5 lbm) | 4.5 kg (9.9 lbm) |
| * optional feature | (All specifications above based upon 100:1 Harmonic reduction drive) | |

**Table 1: Present Actuator Module Specifications**

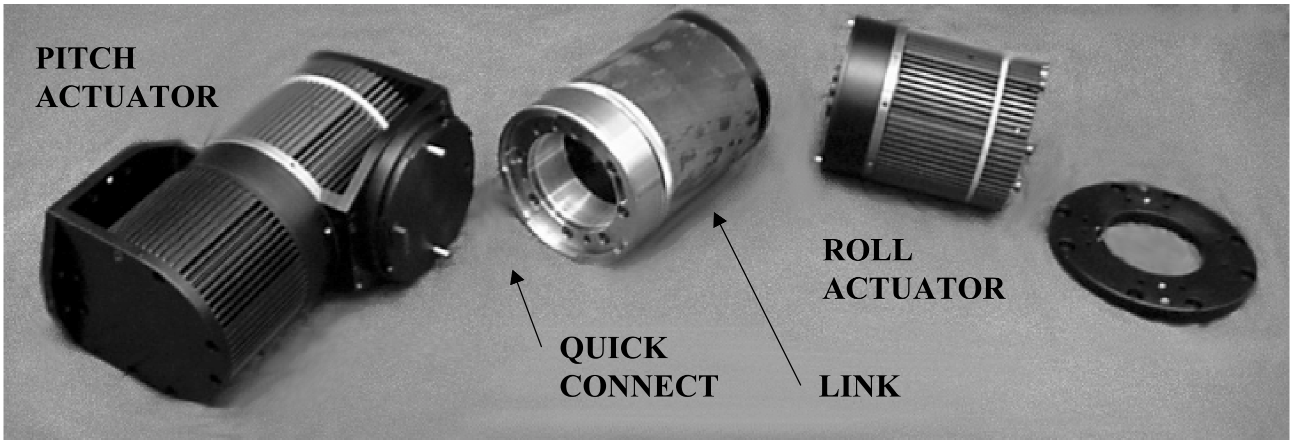


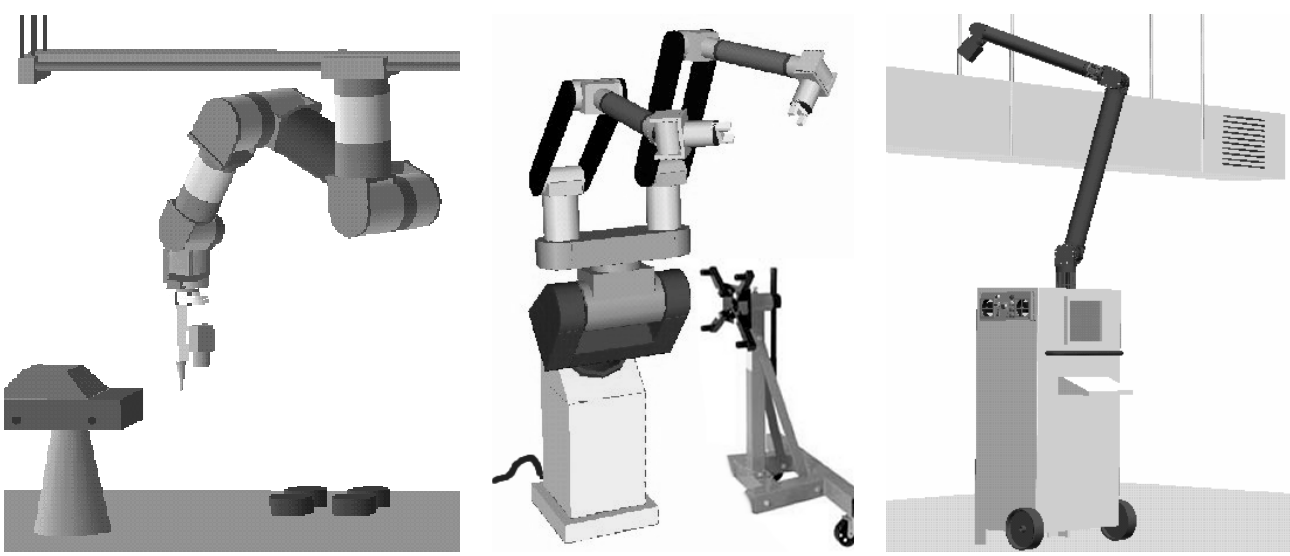

**Figure 4: Several Elements of the Modular Manipulator System**

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 2 consecutive pitch modules.

Each custom robotic manipulator is designed based upon specifications of payload, speed, reach and any kinematic constraints which must be placed on the system. Special considerations such as portability may require the use of quick-connect interfaces between modules. 6-DOF *on Track* *Dual-Arm Manipulator* *Long-Reach, Light-Duty Arm*

Figure 5 shows some possible manipulator configurations.

Once a manipulator is constructed, interfacing to the hardware requires a single cable approximately ½" in (12.7mm) diameter, which carries complete power and signals for all joints to the base flange from the system controller. This system controller contains an industrial 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 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 under this project, Cimetrix system control software has been selected to provide the ability to program, run simulations and provide a graphical user interface.



***6-DOF on Track*** ***Dual-Arm Manipulator*** ***Long-Reach, Light-Duty Arm***

**Figure 5: Multiple manipulator configurations built from ARM modules**

In order to allow safe and efficient field serviceability for EM applications, a novel quick-connect mechanism was created so that actuators can easily be joined with or separated from adjacent modules.(see Figure 6) Within a single quick-connection, electrical, mechanical and pneumatic connections modules are made simultaneously. These interfaces are capable of generating the high internal forces required for stiff and strong structural connections without special tools or more than the effort required to open a typical condiment jar. Quick-connects are extremely simple to operate and have no pinch points which would present a hazard to gloves and other worker protective barriers.

The two halves of each quick connect flange are joined by orienting the two flanges such that electrical connectors and dowel pins are aligned, mating the halves together and rotating by hand a knurled interlocking collar through approximately 45° of rotation. 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 collar.

**Figure 6: ARM Quick Connect Mechanism (open/closed)**

## Resulting Manipulator System

This project culminates in two manipulator systems built using the modular approach developed by ARM Automation. The first manipulator design is configured for a completely generic glove box handling application and is intended to demonstrate and test the full performance characteristics of this manipulator system. The second demonstration system is a simpler manipulator specifically tailored to meet the needs of an application currently under development for canister transfer during the packaging of nuclear materials.

### *Manipulator 1 (6-Axis on Track)*

The first manipulator arm is constructed from 3 larger (ARM32) and 3 smaller (ARM20) actuator modules and is suspended from a linear track.(Figure 7) This 6-axis manipulator serves to demonstrate the high payload, dexterity and performance envelope which can be achieved with this modular system. Such a manipulator would be well suited to material transfer operations within a “double wide” glovebox as shown in Figure 7. This glovebox measures approximately 52” wide by 45” tall by 96” in length. In order to maximize the reach of the manipulator and eliminate the use of “floor space”, this demonstration manipulator is suspended on

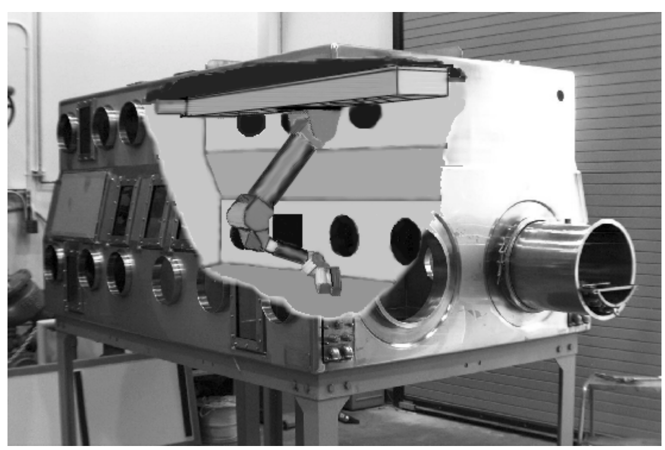


**Figure 7: 6-axis Manipulator in a "Double Wide" Glove Box**

an inverted linear track which spans the length of the glovebox. Payload, speed, reach, dexterity, accuracy, repeatability] Weighing in at just under 32 kg (70 lbm), this 6-DOF arm design has a reach of approximately 1.25m (49") to the tool point and is designed to operate with a 12 kg (26.4 lbm) payload in any pose for an extended period.

This arm is also used to demonstrate system controller enhancements under development by the University of Texas at Austin. These enhancements include manual controller teleoperation and obstacle avoidance. Such enhancements allow the user to operate the manipulator in one of several tele-operation modes without running the risk of collision between any part of the manipulator and objects in its environment.

Finally, this generic glove box manipulator allows ARM Automation to initially demonstrate a complete manipulator installation and repair inside a confined space. By inserting each modular element through glovebox airlocks or ports and mating these elements via integral quick-connect mechanisms, a gloved operator can quickly and safely assemble or replace any element of the system.

**Figure 8: 6-DOF Manipulator**

### *Manipulator 2 (4-Axis)*

The second manipulator to be built from these modules is scheduled to u box testing at Sandia National Labs following testing at ARM Automation. This manipulator design consists of two larger (ARM32) and two smaller (ARM20) actuator modules arranged in a roll-pitch-pitch-pitch configuration. The kinematics of this arm are designed around a hypothetical application for transferring material laden canisters from station to station within one half of a partitioned "double" wide glove box. This 19kg (42 lbm) manipulator design has a reach of 700 cm (27.5") and will be required to move 10 kg (22 lbm) canisters about the glove box workspace.

Many process lines both in nuclear materials handling and in industry, require only a few axes or degrees of freedom to accomplish a given task. As in this case, a 4 DOF manipulator is deemed sufficient to move vertically oriented canisters from station to station. The geometry of this manipulator was selected to allow it to replace a Fanuc LR-Mate manipulator which is currently being evaluated for this task. In addition to providing the maintenance benefits which come with this modular approach, this manipulator will offer a much larger payload (3 X) than the LR-Mate, weigh half as much and provide a 30% greater reach, eliminating the need for the work-arounds required to locate canisters using the LR-Mate. [Fanuc]

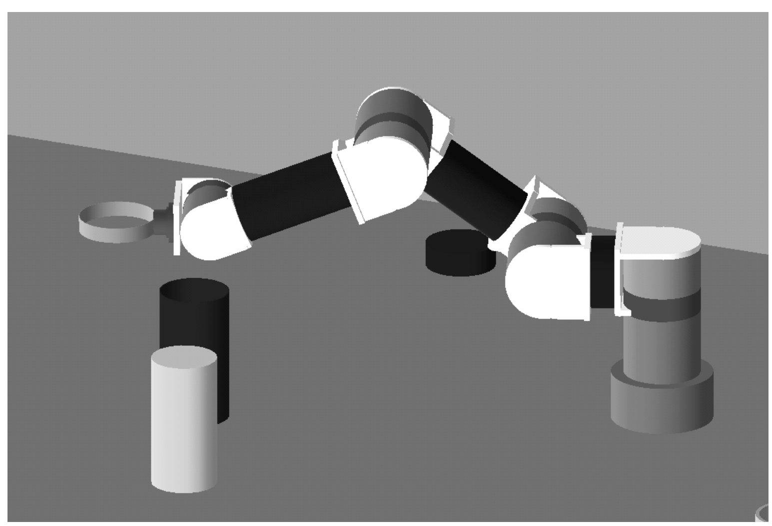


**Figure 9: 4-DOF Canister Handling Robot**

Beyond independent evaluation of the system by a third party, this scheduled cold testing will provide an opportunity for DOE trained personnel to complete qualified bag-in and bag-out procedures on the modular system and examine the operational benefits provided by this modular approach. With this testing complete, other EM groups will then have an opportunity to compare the performance of this system with their needs.

#### *Extra Manipulator (3-Axis on Track)*

An additional manipulator was built from these modules during the course of testing at ARM Automation. This small manipulator design consists of three of the ARM20 actuator modules arranged in a pitch-pitch-pitch configuration and mounted on a linear track. The kinematics of this arm are designed around a hypothetical application for transferring small samples from station to station within one half of a partitioned "double" wide glove box. This 13kg (28.6 lbm) manipulator design has a reach of 900 mm (36") and is capable of positioning a 4 kg (8.8 lbm) payload within the tabletop workspace.

**Figure 10: 3-DOF on Linear Track**

This 4-DOF manipulator is deemed sufficient to move small payloads from station to station. The geometry of this manipulator was selected to make it suitable for automated sample analysis systems, or industrial applications such as semiconductor wafer transfer.

## Future Activities

The goal of this project has been to build a set of tools which can save EM operations both time and money while reducing worker exposure throughout the DOE complex. Following the completed testing of this robotic product, three things must occur. First, it is the objective of ARM Automation and the Department of Energy to make those designing or implementing robotic automation aware that these tools are now available and assist in their deployment where needed. Secondly, ARM Automation will continue its development of sales to industrial customers, such that sufficient production volumes are achieved as to further reduce the cost of systems and to insure that this product is not reliant upon DOE funds for its continued availability and support. Thirdly, development of this technology will continue to provide a larger spectrum of tools with even greater reliability for addressing the full range of robotic needs across the DOE complex.

There exist many EM applications which are in need of workable solutions to specific robotic automation problems. Some of these focus areas are addressed in [Geisinger]. Examples include dual-arm robotics for decontamination and dismantlement, 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 the larger D&D tasks, would require robots built from one or two larger sizes of actuator module in order to wield large power tools and move heavy pieces of structure.

The implementation of this modular approach to robotic automation within DOE-EM tasks is now underway for one task in particular, 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. Heretofore, this system was greatly limited by the lack of a practical delivery mechanism for positioning the sensor suite near the surface to be examined. Through the use of the ARM Automation 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 by the end of 2001, given continued funding.

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## Contract Information

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