A Modular Approach to Robotic Automation of DOE Applications

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Need

More than ever, the DOE is under pressure to clean-up and deactivate the awesome infrastructure constructed for nuclear weapons production. In addition, the standards for environmental restoration and worker safety are being set at their highest levels ever while budgets are being reduced. To achieve more with less, the DOE must look to new approaches and technologies. Key among these is automation. Some of the advantages offered by automated and tele-operated systems include: reduction of human radiation exposure, performance of previously impossible tasks in hazardous areas (high radiation, confined spaces, hazardous chemicals, unstable structures, submerged areas) and reduction in the time to complete large numbers of repetitive operations (such as material transfer or chemical analysis). Unfortunately, many attempts at implementing automation have either been deemed unfeasible with existing technology or have failed due to the time and cost of creating systems customized to face each of the variety of unique challenges in DOE cleanup operations. In order to address these needs, a new paradigm in automation tools is being developed which will enable the successful deployment of automation to reduce cost and accelerate cleanup activities across many areas of the DOE complex. This paper describes this new technology, how it can impact many DOE cleanup efforts and explains in detail, how it is suited to address the specific needs for one particularly challenging class of DOE application.

Problem

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] at the beginning of this project 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 need for simple field serviceability. Combined, these factors often preclude the practicable use of conventional industrial robots and require that unique and robust manipulators be designed and built for each task.

This presents DOE sites and complexes who are commissioned with cleanup operations with the additional challenge of developing application specific robotic systems to satisfy demanding criteria. The development of custom robotic motion systems requires expertise in the specification and integration of low-level machine components (motors, gears, sensors, etc.), design of custom hardware, complex system control software, kinematics and control electronics. The design process requires skilled engineers to perform low-level design, complex specifications, assembly, programming, debugging and documentation. This process can take months to years, depending on the system. All of this must occur before the automation can begin to be applied to the process. Also, due to their uniqueness and rarity, complete documentation of “in house” systems are difficult or impossible to maintain once the original project engineers have moved on, leaving behind legacy systems.

Once a robotic system is installed into an application, it must be serviceable or removable in the event of failure, which is likely, given the harsh environment and demanding tasks of EM applications. The highly integrated nature of any robotic system makes repairs or modifications difficult. Once a robotic system is contaminated and/or broken down within a hazardous environment, repair and even removal can become highly impractical or impossible. The reasons above, combined with the nation’s desire to accelerate the cleanup process and cut costs while improving worker safety, make existing options for robotic automation no longer tenable.

Solution

Fortunately, there is now a better approach to building custom robotic automation systems. Just as the electronics community has discovered with semiconductors, many complex systems can be built from multiple sub-systems of similar or repeated functionality. By pre-engineering this functionality into a “black-box”, the inner-workings and details of each sub-system are shielded from the overall system design. This allows design engineers to focus their efforts on the final product and its operation without “reinventing the wheel” of each sub-system for each new design.

In the field of automation and robotics, a very common sub-system is one used to generate motion for precise positioning of loads. One example of such a sub-system would be an individual joint within an industrial robotic manipulator. This sub-system consists of a tightly integrated package containing an electric motor, gear train, output support bearings, position sensors, brake, servo amplifier and communications controller. Within the context of this paper, this key building block is referred to as an actuator module.

With regard to the needs of the EM, [Geisinger] and [Black & Grupinski] have shown that while each focus area has unique requirements for robotic automation at a system or manipulator level, their requirements at the actuator level are very similar. Thereby, a modular approach to automation which utilizes a small set of versatile actuator modules could be used to construct a broad range of robotic systems and automation cells suited to EM applications. By providing a pre-engineered, pre-integrated motion system to different robotics users within the DOE, new automation systems can be more quickly created without extensive expertise in motion control or the expense of building custom equipment.

This savings in time, expense and effort to deploy new systems, allows focus and resources to be directed at solving EM specific problems using automation in lieu of building new automation tools. Furthermore, the modular architecture, combined with quick connect interfaces, allows robotic systems to be easily moved or repaired in the field. This is something previously impossible or unthinkable for many automation applications. In all, this modular approach to robotics can reduce overall time and cost to accomplish EM objectives where automation is involved.

Technology

Each product in ARM Automation's line of modular tools is built 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 easily 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 into motion control systems, thereby reducing system size, cost, design, wiring, maintenance and overall complexity.

Each actuator module, motor and interface in ARM's product architecture utilizes this technology. 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.

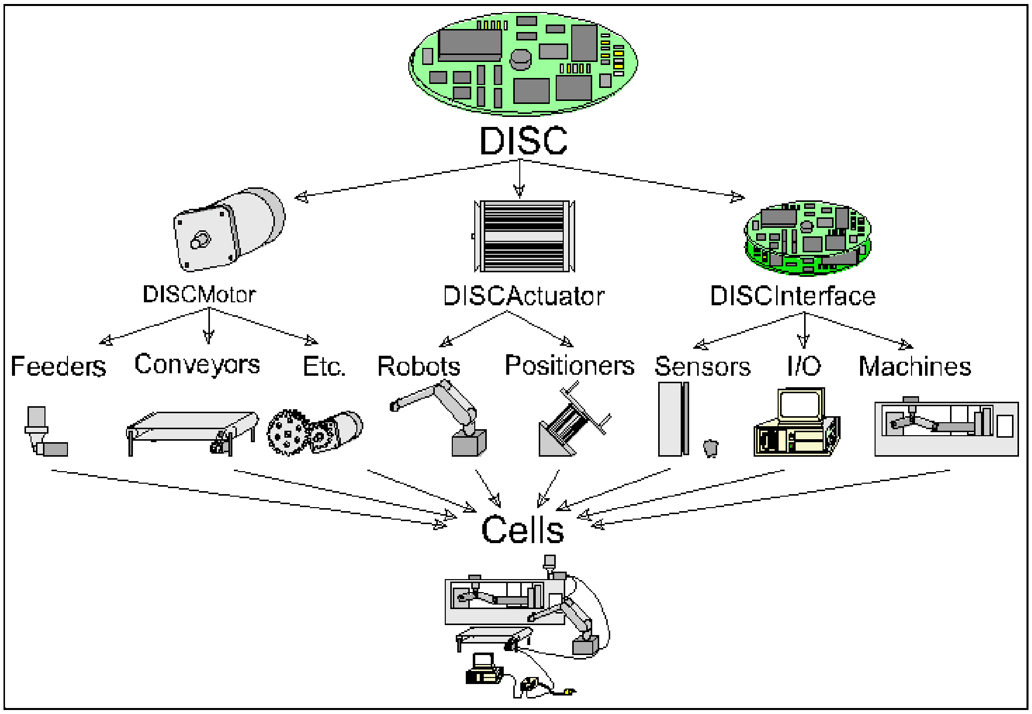

Figure 1: Family Tree of DISC™ Enabled Devices

Each DISC™ device is comprised of two halves. The first is the control and communications board. This control and communications board is then directly mated with an application specific power or analog circuit board suited to a given task. Most commonly, the DISC™ controller is mated with a Power and Sensor Interface (PSI) board of similar proportions to create a high-end servo-amplifier for controlling individual electric motors or actuators. At present, all DISC™ devices utilize an industry standard communications protocol called SERCOS. This open protocol provides deterministic, high-speed communications and is supported by many vendors of motion control components. This token ring architecture allows for a single communications link between all devices under system control.

The classes and sub-types of DISC™ devices are summarized in Table 1. Together with customizable structural links, end-of arm tooling and open architecture system controllers, this small

Class	Sub-Type
Actuators	Rotary
	Linear
Motors	Rotary
	Linear
Interconnections	Links
	Roll to Pitch Adapters
	Quick Connections
Interfaces	Bus Bridges
	General Purpose I/O Modules
	Load Cell Interfaces
System	Controllers
	Power Supplies

Table 1 - Module Classes and Sub-Types

set of components comprise a versatile system from which a very broad range of automation systems can be constructed.

DISC™ controllers are ideally suited for creating actuators in robotic systems. The DISC™ actuator integrates a DISC™ amplifier along with a high performance brushless DC motor, position/torque sensors, gear train, structural bearings, fail-safe brake, and other components to form a powerful pre-engineered actuator package. Each unit is completely sealed to allow wash-down and even submerged use. By utilizing a standardized electro/mechanical interface, actuator modules may be readily combined with other modules, such as links or tools, to construct automated motion systems.

As shown in Figure 2, DISC™ actuator devices can be used to build robotic manipulators. An robotic arm can be assembled in almost any standard or custom kinematic configuration imaginable through the use of a small set of links and yokes (see Figure 3). Link modules are simply tubular or linear extensions of actuator modules in roll, while yoke adapters convert roll modules into pitch joints. Pitch actuators can be thought of as the "bending" point in a serial arm.

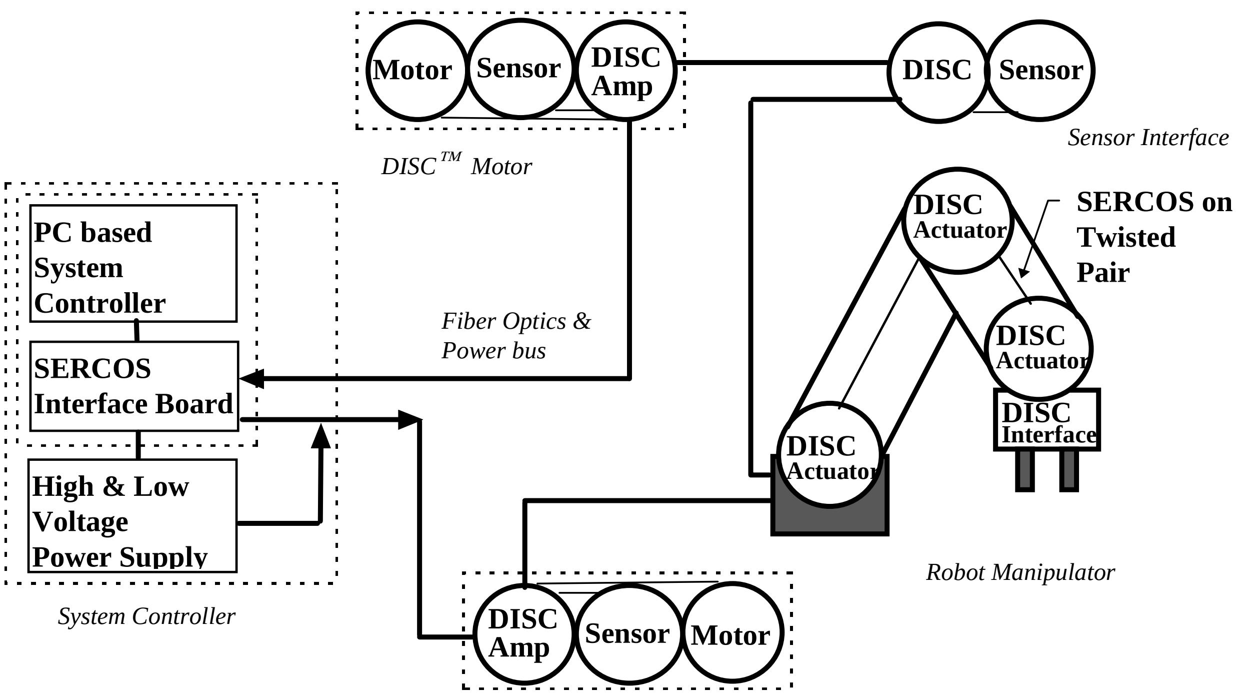

Figure 2 : Simplified Motion Control System Using DISC™ Devices

Variations on yoke adapters allow the creation of pitch joints which are full-offset, in-line, double-yoke or custom offset. Link modules typically take the form of cylinders extending the length of roll actuators, but may also be built as a "parallel-links" for maximum stiffness between 2 consecutive pitch modules.

Each robotic manipulator is custom designed based upon payload, speed, reach, dexterity, Degrees Of Freedom (DOF) and any kinematic (motion) constraints which must be placed on the system by the application. Once these application parameters are determined, a arm's shape, or DH parameters, are selected to best suit the task. Based on the payload and speed, actuator size and gear ratio are selected from the population of standard actuator modules. Standard links or customs are then added to complete the manipulator design.

Interfacing to this robotic hardware requires a single 12-wire cable which carries complete power and signals for all joints from the system controller to the base flange. This system controller contains an industrial PC combined with a power supply in a single bench-top sized enclosure. The

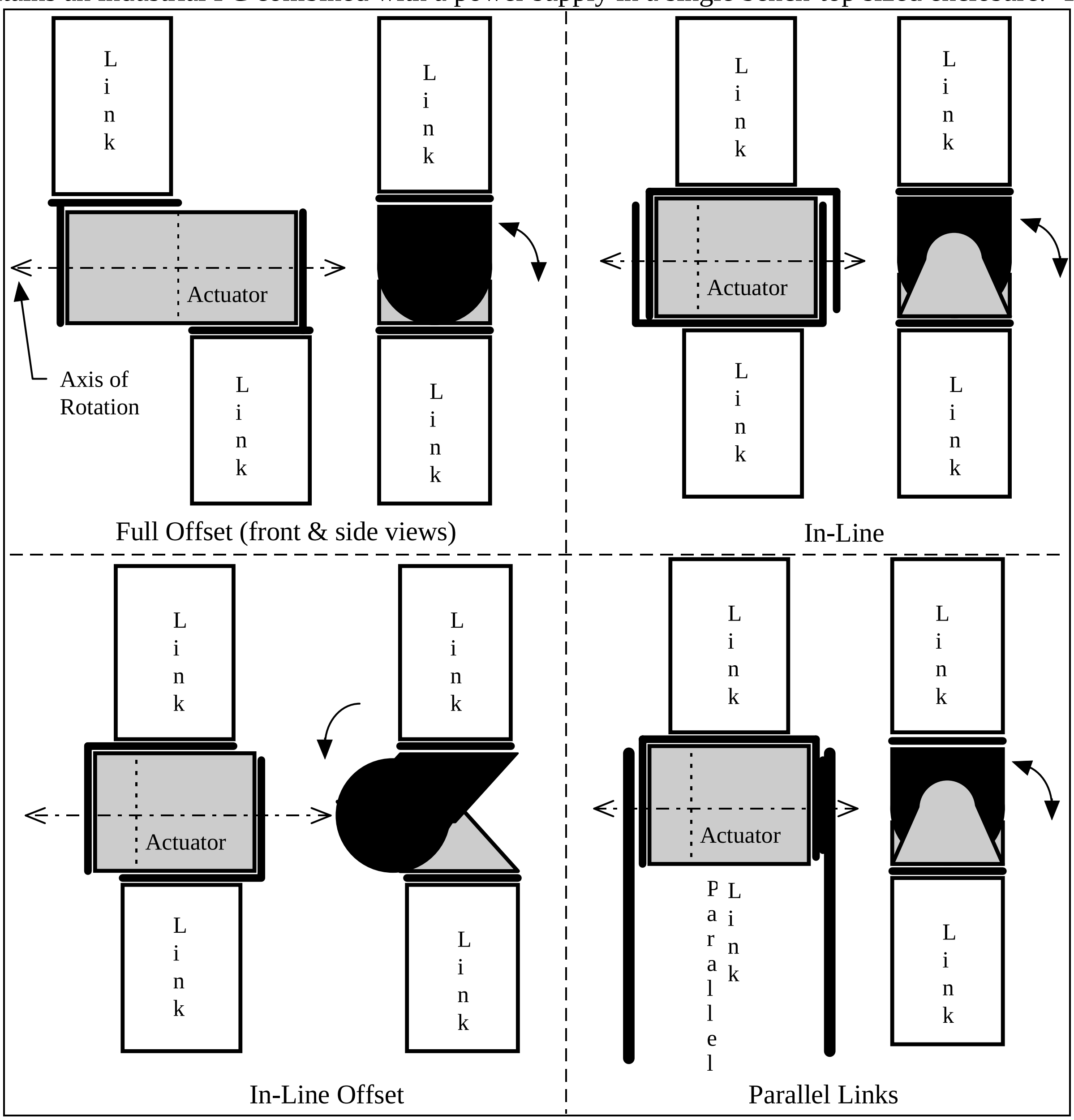

Figure 3: Various Pitch Joints

PC controller is an inherently flexible platform which includes a SERCOS interface board for coordinating axes and issuing 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.

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. 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.

Accomplishments

The focus of this project is to develop two sizes of actuator modules, including controllers, required links and quick connect interfaces for constructing manipulators suitable for DOE-EM tasks of human scale payloads and work envelopes. In addition, these robot systems must also lend themselves to, or meet the following criteria not commonly found in robotic systems:

- Extremely simple field serviceability or quickly replaceable modules
- Customizable kinematics
- Capable of operating in moderate radiation fields and extremely harsh environments
- Human portable module size
- Sealed and/or positively pressurized
- Capable of module bag in/out from a standard glove box

These actuator modules, controllers and supporting equipment have now been designed, built and are currently undergoing performance testing and debugging at the module level. Preliminary data and design specifications for the actuator modules are shown in Table 2.

Design and procurement for ARM Automation's high-density power supply/system controller is now complete and DISC™ amplifiers are being brought on line over the SERCOS communications protocol. This process allows for the improvement and debugging of control code, both at the device level (DISC™) and at the system controller level (Cimetrix).

In addition to the design of controllers, actuator modules and ancillary modules, system level design is near completion. At the system or robot level, final robot kinematics have been determined through computer simulation to optimally satisfy the requirements of the selected demo application (see Application). Manipulator kinematics have also been selected for the demonstration arm which will be assembled at ARM Automation facilities. Work is now underway

	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)	160 mm (6.3 in)
• Diameter	97 mm (3.8 in)	145 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 reduction drive)

Table 2: Actuator Module Specifications

to construct a glove box mock-up which will allow preliminary testing of this in-house demonstration manipulator.

In order to meet the unique requirements presented by field service under hazardous conditions, quick change out connections between modules were deemed essential. These interfaces have been designed, prototyped in multiple forms and tested. Initial testing and feedback from personnel within the DOE complex has indicated that these devices will safely allow workers wearing even the heaviest of protective gloves to quickly assemble and disassemble an entire robot using only two hands and a simple spanner wrench. These findings will be verified during later testing by DOE personnel.

Application

This project culminates in two manipulator systems being built using this modular approach. Due to the scope of this project, both of these systems target material handling applications within glove box environments. The first manipulator design is targeted at a completely generic glove box handling application and allows the full performance characteristics of this manipulator system to be demonstrated. This arm is constructed of 3 larger (ARM32) and 3 smaller (ARM20) actuator modules suspended from a linear track inside a glove box mockup. This 6-axis manipulator serves to demonstrate the high payload, dexterity and performance envelope which can be achieved with this modular system. Weighing in at less than 32 kg (70 lbm), this 6-DOF arm design has a reach of approximately 1.25m (49”) to the tool plate and can hold a 12 kg (26.4 lbm)payload in any pose for an extended period. This arm will also be used to demonstrate system controller enhancements under development by the University of Texas at Austin. These enhancements include manual controller teleoperation and obstacle avoidance. Finally, this generic glove box manipulator will allow ARM Automation to initially demonstrate a complete manipulator installation and repair inside a confined space.

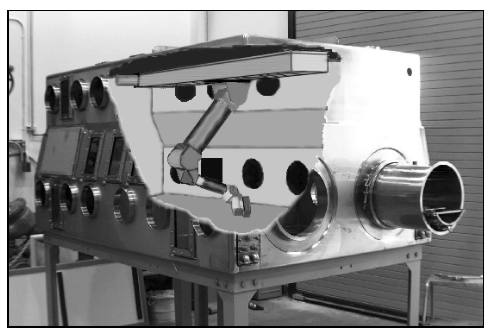

Figure 4: 6-DOF Manipulator in a "Double Wide" Glove Box

The second manipulator to be built from these modules is scheduled to undergo "cold" glove box testing at Sandia National Labs. This manipulator design consists of three larger (ARM32) and one 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 a "double" wide glove box. This 21kg (46 lbm) manipulator design has a reach of 700 cm (27.5") and will be required to move 12 kg (26.4 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. Other "robotic" tasks within process lines may only require 2 or 3 DOF of functionality. Again, the modular approach lends itself to these automation applications without the complexity, cost and space required of conventional 5 or 6 axis robotic systems.

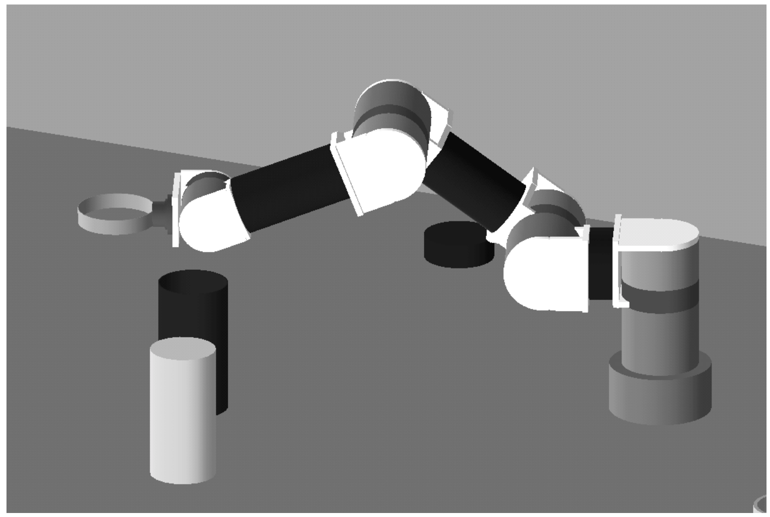

Figure 5: 4-DOF Canister Handling Robot

Beyond independent evaluation of the system by a third party, this cold testing will provide an opportunity for DOE trained personnel to complete 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.

Future Activities

The goal of this project is to build a set of tools which 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 responsibility 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 pursue uses of this product within industry, 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 must continue to provide a larger spectrum of tools sufficient to address 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 for remote inspection or 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. Such applications would also benefit from joint torque control which has been planned for in this product architecture, but like the larger actuator module sizes, was outside the reduced scope of work.

Finally, while the actuator modules, controllers and ancillary components created under this project have been designed for maximum radiation tolerance without the use of specifically "hardened" components, "hot" testing of these devices is in order. This will quantify the tolerance of the existing design to different forms of nuclear radiation, while providing information necessary for design improvements, if any are deemed necessary.

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Contract Information

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