

Evaluation of State-of-the-Art Manipulators and  
Requirements for DOE Robotics Applications  
Topical Report

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## **Abstract**

This report provides an overview of applications within the DOE complex which could benefit from the use of modular robotics technology during remediation operations. Each application area contains one or more specific tasks which are presently conducted by humans under hazardous conditions or which are deemed highly impractical, or are altogether impossible without automation. Five major areas were investigated for specific needs with respect to automation. Information was collected on Mixed Waste Operations, Contaminant Automated Analysis, Tanks, Decontamination and Dismantlement and Automated Plutonium Processing. During this investigation, information was gathered from available literature, telephone interviews with informed personnel and on-site visits. This data serves to provide design requirements and guidelines for the design of a family of modular actuators, which will be used to construct manipulators suited to each task.

In addition, a survey of existing modular manipulator designs is presented. This survey addresses modular manipulators developed inside government labs and in universities for such applications as space exploration or controls research. It also addresses efforts at commercially viable industrial manipulators which have been built. This survey of robotic systems provides the reader with a glimpse into what technology currently exists in the way of modular manipulator automation and, to a degree, where this technology may be applicable or, more often, where these systems are unsuited to EM applications.

From the information gathered during this study, it is possible to sufficiently define the requirements of one manipulator system which can be used to conduct automated transfer operations within Plutonium gloveboxes. This manipulator will be constructed from ARM Automation actuator modules and will provide this application with a viable option for automation within these gloveboxes. The design issues surrounding this manipulator and its specifications are discussed in the final portion of this report.

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# **1. Introduction**

This report has been prepared as one of the first tasks in the development of a modular robotic manipulator for Automated Plutonium Processing (APP). This effort came about in response to a proposal submitted early in 1997 which outlined an approach for utilizing a system of five intelligent actuator modules to construct two manipulators: one tailored to the needs of Dismantlement & Decommissioning (D&D) and the other to APP. Key arguments for employing a modular approach were shorter timelines, simplified repair and reduced life-cycle costs from a technology which can be applied to multiple automation tasks within the DOE complex.

While the focus of the project has been concentrated on APP, we believe it is important to initially examine the needs of the other DOE applications to ensure that the module designs will be applicable to applications other than APP. Thus, the first objective in preparing this report was to provide an overview of the automation needs of key DOE applications within the context of modular automation. As such, this report is the beginning of a roadmap outlining how modular robotic systems could be applied to DOE automation applications. An in depth study of all DOE's automation needs was deemed impossible, however, an overview which provides sufficient information to facilitate the design of a versatile set of actuator designs has been achieved. This has been accomplished by a review of literature, telephone conversations with automation experts and on site visits within the DOE complex.

A second objective is to provide a brief survey of previously developed technology in the area of modular robotics and the current state-of-the-art in Plutonium glove-box operations.

The final objective of the report is to provide a detailed analysis of the APP manipulator requirements with the result being a set of preliminary design specifications and implementation suggestions. In this process, the needs of two main APP areas were considered: 1) Generic APP tasks for applications such as in-box processing and stabilization of residues and separation of Plutonium laden materials and 2) Disposition of Plutonium pits from excess nuclear. A key factor in considering the second area was the relatively abundant amount of information available on the ARIES line and it's relatively short timeframe for production deployment. Along with the general requirements of other DOE applications, the APP requirements are used to map from manipulator, or "system level," requirements to actuator level specifications.

In its second revision, this report was used as the foundation for the presentation and discussions at the project kick-off meeting hosted by The University of Tennessee at Knoxville on Tuesday, August 25th. As a result of these discussions, several minor changes have been incorporated into the final version of the report. The state-of-the-art manipulator survey has been enhanced, particularly with regards to Robotics Research and the requirements for tele-operation have been modified based upon input from Dennis Haley of The University of Tennessee and Mark Knowkes of Oak Ridge National Laboratories.

## 2. Survey of Modular Robotics

This section provides an overview of modular robotics technology by addressing developments in the field. This report defines robotic modules as robots comprised of mechanically separable joints having Degrees-Of-Freedom (DOF) less than that of the entire manipulator system. These systems may or may not have integrated cabling and/or electronics. The information given below summarizes the most prominent modular robotic concepts which have been built to date. These concepts are broken down into three categories: Government/Space robots, University Research Manipulators, and Commercially Available Manipulators. Each of these classes are discussed below.

### 2.1 Government/Space Robotics

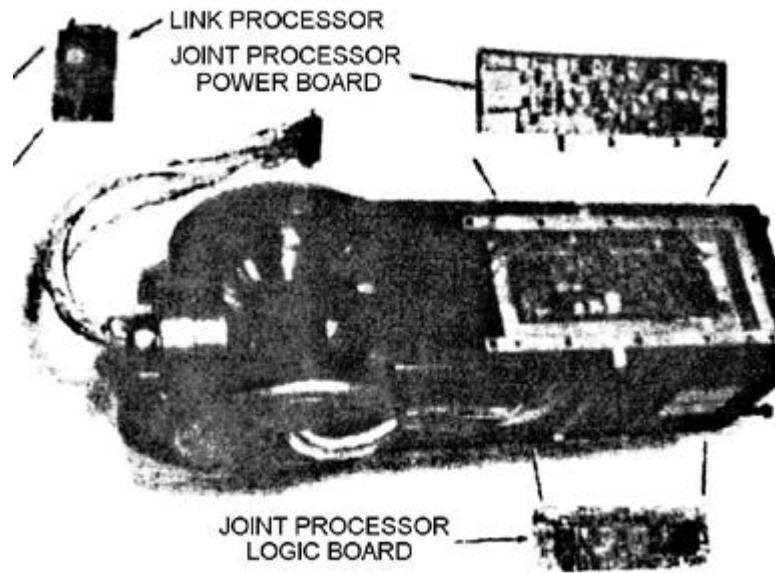
This section details the Advanced Telerobot (AT), Laboratory Telerobotic Manipulator (LTM), and the Flight Telerobotic Servicer (FTS). The first two systems were developed out of Oak Ridge National Laboratory (ORNL) and last was developed by Martin Marietta for NASA.

#### 2.1.1 Oak Ridge National Laboratory - Laboratory Telerobotic Manipulator (LTM)

[Glassell] presents the development of the LTM which appears to be related to the AT system described in 2.1.2. The use of modularity in this design was driven by on-line repair and replacement. [Hamel] This design uses distributed control electronics to minimize wiring and two different sized pitch-yaw differential joints to build a 7 DOF manipulator. [Glassell] gives little mechanical detail other than the joint modules utilize traction drive transmissions. The joint controller consists of two PCBs, a logic board and a communications board. The characteristics of the controller are listed in Figure 2-1.

Component	Function
10 Mhz Intel N80C196KA	CPU
16KB of programmable ROM (PROM)	Store start-up and communications code
16K of static RAM (SRAM)	Store applications code
Altera EP600LC programmable logic array	Address decoding
Intel N82588 local area network (LAN) controller	Communicate at 2-Mbaud over fiber optic bus
Five Analog Devices AD2S82JP 16 bit resolver-to-digital chips	Two are used for each of the pitch and yaw resolvers and one for the roll resolver
Two Texas Instruments THCT2000FN quadrature decoder chips	To decode quadrature signals (512CPR) from encoder located on motor shaft
Two Analog Devices AD524CE instrumentation amplifiers	Amplify torque signals
Two Analog Devices AD7672KP05 analog-to-digital (A/D) converters, AD585JP sample and hold buffer and an AD7502SE four-channel multiplexer and a Maxim MAX358CWE eight channel multiplexer	Convert analog torque, motor velocity from a tachometer, joint velocity and master manipulator hand controller signals to digital.
Motor Bus Voltage	24 V
Misc	Brake relay control and RS-232 interface.

**Figure 2-1- Laboratory Telerobotic Manipulator - Controller Components**



**Figure 2-2 - LTM @ DOF Module [Geisinger]**

The logic board is a 2 by 7 inch, 8 plane, double sided PCB with 39 surface mount devices (SMD). A single, bi-directional, 2 MB/s [Hamel], fiber-optic link is used as the communications medium. All cabling is routed internally using a custom ribbon cable rated for more than one million flexing cycles and manufactured by W.L. Gore. Note that unlike some of the other systems described in this section, this manipulator does not have the power electronics in the joint. The integrated electronics package acts solely as a data collection and communication unit. The amplifiers are located at the base and individual wires are run to each joint (the ribbon cable contains a total of 20 wires). The electrical connectors are configured such that changing the serial order in which the joints are connected does not require any hardware modifications. As a result, the wire count passing between modules was 52 compared to 5 for the AT system.

### **2.1.2 Telerobotics International and Oak Ridge National Laboratory - Advanced TeleRobot**

[Martin et al] describe the development of a mechanically and electrically modular manipulator with a distributed control system called the Advanced TeleRobot (AT). This design is an evolution of the LTM. A major difference is the replacement of the traction drives with gears. [Hamel] The primary motivation for adopting a distributed control strategy was experience that showed the handling and maintainability of telerobotic systems is limited by the large cable bundles consisting of between 50-100 insulated conductors. Two sizes of dual axis module designs and a roll/tong module are used to construct a 7 DOF manipulator. The joint modules use a differential drive system and can be used in either a pitch/roll or pitch/yaw configuration. The same size module is used for the wrist and elbow, while a larger module of similar design is used for the shoulder. The control electronics are located within each module and are identical in all four modules. Each electrical connector is identical to allow for easy

replacement and rearrangement. Six conductors connect each module, two for a high-speed RS-485 bus, two for motor power and two for digital logic power.

Function	Attribute
CPU	Intel 80c196 microcontroller
RAM	64K RAM
ROM	8K ROM
Communications	RS-485 at 750 Kbaud
PWM Controller	ASIC designed to generate dual PWM signals to control 2 motors operating at 23.44 KHz
Motor Position Sensors	Incremental Quadrature Encoders
Output Position Sensors	Resolvers
AtoD	4 Channels of 10 Bit Resolution
Motors	Brush
Bus Voltages	+5 V (Logic), +24 V (Motor)

**Figure 2-3 - AT controller Specifications.**

The controller itself consists of 3 circular PCBs, the joint processor card, the I/O card, and the amplifier card. Figure 2-3 contains the details of the AT system. An Application Specific Integrated Circuit (ASIC) which produces the PWM signals was designed to minimize the size of the controller. The total controller package volume is 5.08cm high by 10.16cm in diameter.

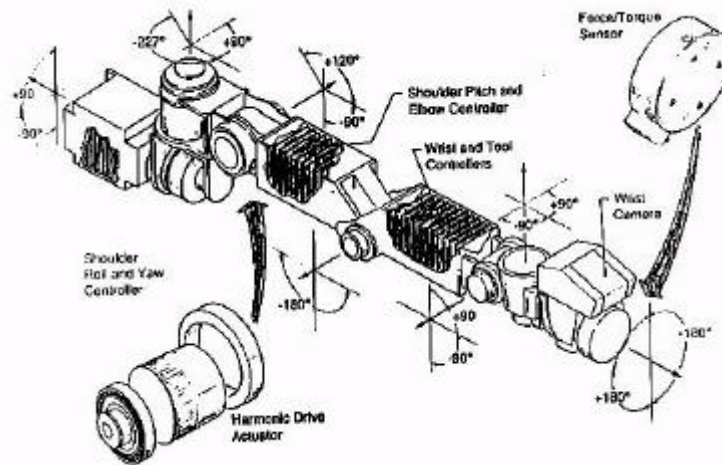
This is one of the first designs to incorporate a customized embedded controller. This resulted in a very compact architecture which is a requirement for any modular manipulator. Since 1988, when this work was done, standard microcontrollers with on-board PWM circuitry have become available. These devices further reduce the size of the controller and eliminate the need for a separate PWM ASIC chip.

### 2.1.3 Martin Marietta/NASA - Flight Telerobotic Servicer (FTS)

The FTS project [Lowery and Shattuck, 1992] [Andary and Spidaliere, 1993] was conceived to develop a seven DOF manipulator (shown in Figure 2-5) to provide a safe alternative to human presence in space. Many of the complex issues in this project were related to safety considerations of operating in space. Modularity was not a main design goal of the FTS project, but it is described here because it incorporates distributed controllers which are critical for the implementation of modular robotics.

Parameter	Specification
Reach	1.68m
Shoulder roll pitch and yaw actuator torque output	160 N*m (1416 in*lbf)
Elbow pitch actuator torque output rating	83 N*m (735 in*lbf)
Wrist yaw, pitch and roll torque output rating	33 N*m (292 in*lbf)
Motor Bus voltage	120V DC
Geartrain	100:1 ratio harmonic drives
Output position sensors	Inductosyn (20-22 bits)
Cabling	33 layer flat cables w/ 500 conductors

**Figure 2-4- Key FTS Specifications**



**Figure 2-5 - FTS Manipulator**

Three joint controllers were embedded within the links of the manipulator; one each for the shoulder, upper arm and lower arm. Each controller consisted of a CPU with an Intel 80386, 512KB of RAM, an I/O board, a power supply board a DC motor drive board and an acquisition board. A MIL-STD-1533B bus was used to communicate with the embedded controllers. The low speed of this bus resulted in low control frequencies of only 50 Hz. Figure 2-4 summarizes the key features of the FTS system. Unfortunately, given the strict demands for fault tolerance the main advantage of the distributed approach, reduced wiring, was partially negated. For instance, the wire count at the base module exceeded 500 wires.

## **2.2 University Developed Modular Robotics Systems**

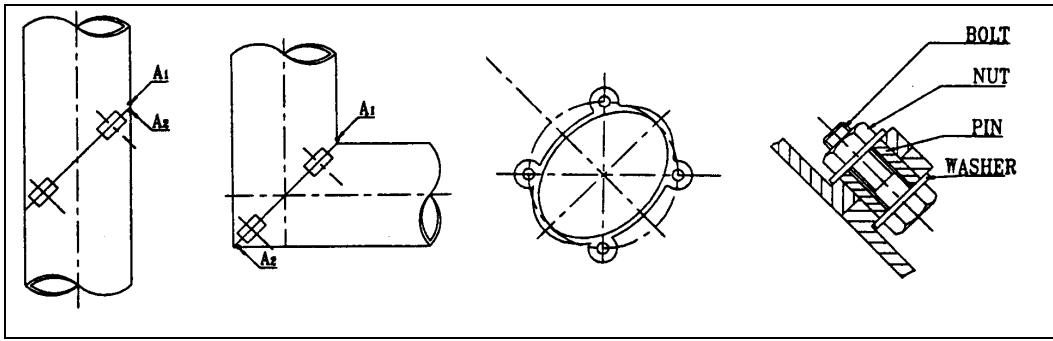
This section presents modular robotics designs which were studied at Carnegie Melon University and at The University of Toronto.

### **2.2.1 The University of Toronto - Modular Robot Designs**

#### **2.2.1.1 Benhabib design**

Benhabib designed a set of robotic modules with the main goal of minimizing module inventory by maximizing module flexibility. [Benhabib et al, 1990] [Benhabib and Dai, 1991] [Benhabib et al, 1992] This is extended to a requirement that any module should be connectable to any other module regardless of type and size. The aim of this design was to enable straight (roll) and perpendicular (pitch and yaw) connections without additional hardware or modules. This design eliminated all quick release mechanisms based on the assumption that they need not be stiff or accurate and developed the bolt together flange shown in Figure 2-7.

By arranging successive joint and link modules of this type in both the straight and perpendicular configurations, many different type of manipulators can be constructed. Two sizes of main joints have been designed; a large size for positions near the base and a small size for distal joints. Harmonic drives have been selected for their high reduction ratio, very low backlash, high efficiency and fair accuracy.



**Figure 2-6 - University of Toronto Joint Connection [Benhabib et al, 1992]**

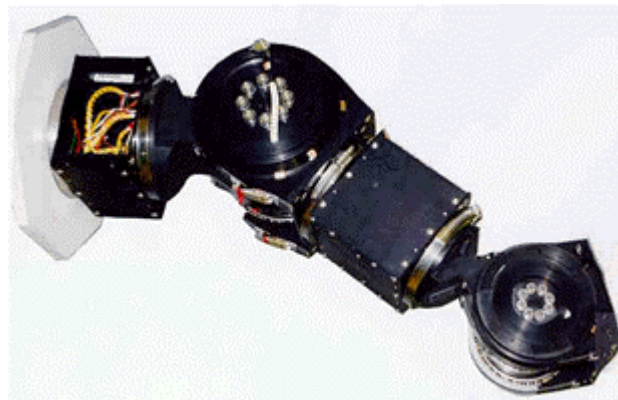
Parameter	Large Joint	Small Joint
Rated Torque	400 N*m	200 N*m
Gear Ratio	60:1	60:1
Mass	15 kg	8.5 kg
Max. Speed	57.2 rpm	57.2 rpm

**Figure 2-7 - University of Toronto Modular Joint Specifications**

### 2.2.1.2 Goldenberg/ESI

Another set of modular robotic joints has also been developed at The University of Toronto in the Robotics and Automation Laboratory by Dr. Andrew Goldenberg. This system (shown in Figure 2-8) utilizes off the shelf PC-104 technology for its motor's controllers and amplifiers. The PC-104 boards (3.6" by 3.8") used to control the joints are located in the links adjacent to the joints. This design is commercialized by Engineering Services Incorporated (ESI). ESI sells the modules in 4 sizes. Some key specifications for these systems are depicted in Figure 2-9 - ESI module characteristics

Because of the size of the PC-104 boards, the overall size of a typical 6 DOF manipulator is limited to a minimum length of 1.2 meters. The maximum payload for such a system is limited to 4 kg.



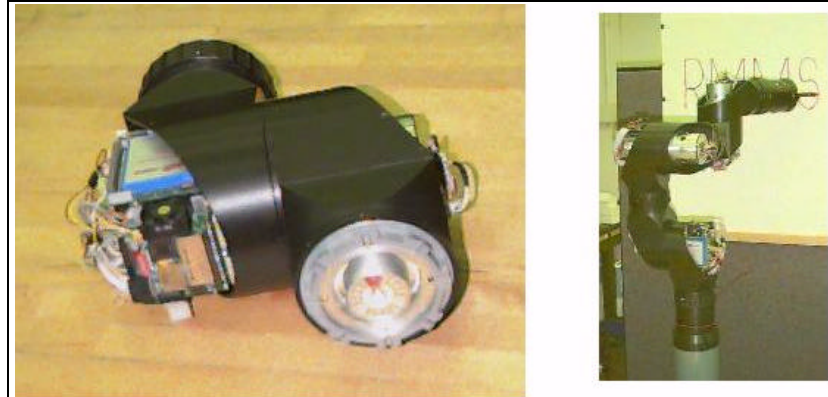
**Figure 2-8 - ESI Modular Concept**

Joint Power/ Parameter	240 W	180 W	90 W	60 W
Rated Torque	210 N-m	70 N-m	20 N-m	10 N-m
Max Speed	20 RPM	20 RPM	20 RPM	20 RPM
Processor	386 SX PC-104 System			
Communication	Ethernet 10BaseT (10 Mbaud), RS485 (115 Kbaud)			
Voltage	80 V	48 V	48 V	48 V
Geartrain Topology	Harmonic Drive			

**Figure 2-9 - ESI module characteristics**

### **2.2.2 Carnegie Mellon University: Reconfigurable Modular Manipulator System (RMMS)**

The RMMS design, shown in Figure 2-10, is based upon a set of interchangeable link and joint modules to allow a system to be built up in multiple configurations. This system incorporates electronics in both the links and joints which stores the kinematic information about the module. The electronics in this system are a combination of custom and off-the-shelf components.



**Figure 2-10-RMMS Joint Module and Manipulator**

RMMS represents a substantial effort to develop a modular robotic concept. RMMS is the mechanical hardware component of Carnegie Mellon's rapidly deployable manipulator system which also includes modular software. [Paredis and Khosla, 1996] Four types of modules have been built: base, link, pivot (pitch) joint and rotate (roll) joint. The pitch and roll joints use the same internal components and only differ in the housing. These modules incorporate many of the features required for a truly modular system including: a bus based communication system to communicate with controllers and amplifiers located in the modules, a quick-connect, integrated electrical and mechanical interface, and sensors to determine the configuration of assembled modules. Figure 2-11 summarizes some of the key aspects of the RMMS system.

When used in a passive module (link or base) this controller identifies the module to the system controller by providing a serial number and interface orientation information. When used in an active module, additional daughter cards are added. For the joints discussed above, one daughter card, containing a Resolver-to-Digital converter and an D/A converter, is added. The D/A converter is used to provide an analog command signal to the Galil amplifier. For two-degree of freedom modules, an additional daughter card and amplifier are added.

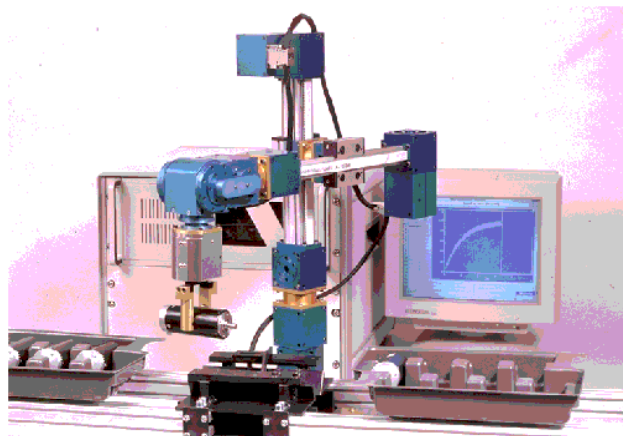
Parameter	Specification
CPU	80C166
Actuator torque output	270 N-m (2390 in*lb)
Max. Output Speed	14.3 RPM
Motor Power Amplifier	Off-The-Shelf Galil P/N SSA-8/80
Coupling	Integral electrical/mechanical interface with locking ring
Communications	2 RS-485 and four video buses
Communication protocol	ARCNET at 5 Mbaud
Motor Bus voltage(s)	72V DC & 48 V DC
Geartrain Topology	100:1 Harmonic drives
Output position sensors	Resolvers
Cabling	30 conductors plus pneumatics

**Figure 2-11 - Key RMMS Specifications**

## **2.3 Commercial Robotics**

This section details the PowerCube, Robotics Research and the URSULA manipulators. These manipulators have been developed or have been commercialized by industry and are, or have been, available for sale to industry.

### **2.3.1 Electro Pneumatic Innovations - PowerCube**



**Figure 2-12 - PowerCube Manipulator**

Function	Attribute
Motor Bus Voltages	24 V, 48 V
Power Range	100 to 500 VA
Geartrain Topology	Harmonic Drive
Communications	CAN (2 MBaud), RS-485 (115 Kbaud)
Position Sensors	Incremental Quadrature Encoders
CPU	16 Bit Microcontroller
Motors	Brushless DC

**Figure 2-13 - Powercube Specifications**

Figure 2-12 shows a manipulator assembled out of the PowerCube modules. This design was developed by Dr. Sawa Tschakarow in Germany and licensed by Electro Pneumatic Innovations. This architecture currently has developed three 1-DOF rotary modules, two 1-DOF linear modules, and two 2-DOF wrist modules. The control electronics are located within each module and are similar in all three module topologies. Each electrical connector is identical to allow for easy replacement and rearrangement. Unlike all other systems reviewed herein, this system runs the cables externally between the joint modules. Figure 2-13 contains some of the details of the PowerCube system.

### 2.3.2 Robotics Research Corporation

The Robotics Research Corporation offers a line of force/position-controlled, modular, electric manipulators for use in man-equivalent robotic and telerobotic applications. Their current offering is based upon several generations of designs and thus is the most highly refined of the systems reviewed in this report. They have created kinematically-redundant ( $> 6$  dof) robots from these modules which are currently used for research purposes at NASA, universities and several other government laboratories. The most notable attribute of these devices lies in their capacity for internal force sensing. This allows RRC manipulators to enact more precision and quick-response in force control.

Actuator modules are connected using V-band clamps and independent electrical connectors which pigtail out from the open ends of each joint. In the most recent revision, power and control electronics reside in adjacent links or base. This approach to distributed control reduces the overall system power and communications umbilical, however, it generates additional connectors and pigtails at each interface and requires that room be allocated for electronics packages within directly adjacent links. While its modularity facilitates customization, this architecture is not readily field interchangeable, or particularly, reconfigurable.[RRC]

There are several distinctions between the Robotics Research designs and those to be

Function	Attribute
Motor Bus Voltages	24V and 160V
Torque Range	2.8-4,858 N-m (25-43,000 in-lb)
Geartrain Topology	Harmonic Drive
Position Sensors	Geared Resolvers
CPU	DSP
Brake	Fail On
Motors	Brushless DC

**Figure 2-14- Robotics Research Generic Manipulator Specifications.**

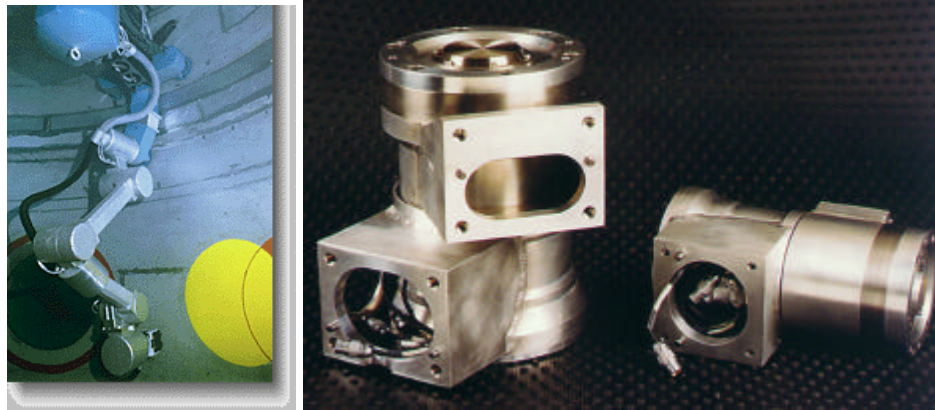
developed under this project. The most significant is the location of the control and power electronics and the associated wiring. By tightly integrating the electronics within the actuator, the number of wires and thus the size of the connector between modules is reduced such that it may be mechanically integrated into the flange. With this approach, both the mechanical and electrical connections are made simultaneously thus simplifying module repair and replacement. Robotics Research's module designs are ideally suited for constructing custom multi-DOF serial manipulators at the factory. In comparison, the actuator architecture to be implemented for this project will not be as robot centric and will be designed for ease of reconfigurability in the field rather than the factory.



**Figure 2-15 - Robotics Research Dual-Arm Manipulator**

### **2.3.3 Framatome Technologies: The URSULA Manipulator**

Framatome Technologies developed the URSULA manipulator for Reactor Vessel Inspection. The URSULA Manipulator (see Figure 2-16) is designed around a building block, which like the RRC system, is modular and serviceable at the point of manufacture. URSULA contains all the control electronics in the base of the manipulator which minimizes the number of wires in the tether required for deployment in reactor vessels. The overall mass of URSULA is around 800 pounds with a reach of 6 feet. Framatome Technologies uses the mechanical module to form another robot used for pipe inspection, thus, demonstrating the benefits of reuse gained from developing a modular architecture. The positional sensor used in these modules is a resolver.



**Figure 2-16 - Framatone Technologies Modularity Concept [Framatome]**

## 2.4 Conclusions

There exist several basic choices which are made during the design of modular actuators for robotics. Combined, these choices serve to define the architecture and the ability of each system. The first choice involves the location of relative motion at either the center or end of the unit. The center split leads to a more versatile unit, while the second method is more compact. Control, power, and communication electronics can either be located in the modules, in the link, or externally. Modular designs must provide modular connections which can take many forms, each with its own degree of usability. All designs surveyed used harmonic gear trains, except for the AT design. Output positional sensors may be of several types, with the incremental encoder being the most common.

	Electronics	Communications	Quick Connect	Actuator Split	Position Sensor	Wire Count
AT	ASIC in dual joint	RS485-@ 750K baud	Bolt flange	End	Incremental quadrature encoders	6+
LTM	Communications data and in joints	2 MB/s over fiber bus	Bolt flange	End	Quadrature encoder + Resolver	52
FTS	In links	Mil STD 1533 Bus (2 MHz)	Bolt flange	End	Inductosyn	500+
Benhabib	No	NA	Bolts	Center	NA	NA
ESI	In links	Ethernet 10 Base T	Bolts	End	Incremental encoder	12+
RMMS	In joint	Arcnet (2-RS485 and video busses)	Collar	Center	Resolvers	30+pneumatics
EPI	In joint	CAN and RS-485	Bolt flange	Center	Quadrature encoders	NA
Robotics Research	In adjacent link modules	NA	V-band and plugs	Center	Geared resolvers	NA
Framatome	In base	NA	Bolt flange	Center	Resolver	High

**Figure 2-17 - Summary of Comparable Information**

Due to the lack of available information, this survey has not addressed one of the most important factors regarding each of these technologies. As many manipulator development projects have found, while it may be possible to build a system to perform, without significant effort and planning, the cost of deployment for any robotic system is likely to be unacceptably high. This cost of production is directly related to the amount of custom components, complex machined parts, integration effort, special software and other unique aspects of each design. If any modular robotic solution is to be successful, it must be reproducible at practical costs.

In summary, previous and existing modular manipulator designs have demonstrated and explored several aspects and concepts available to future systems. Despite operational and some successful designs, no system surveyed, holds the necessary attributes for a viable DOE multipurpose automation system. In general, this is because these systems fall short one or more of the following areas: payload, reach, flexibility, size, field serviceability and/or life-cycle cost. It is therefore apparent that if cost effective robotic solutions are to be deployed and operated in hazardous DOE-EM applications, a new more suitable solution must be made available.

### **3. DOE Automation Applications Overview**

This section provides an overview of the major DOE automation applications outside of APP. Each application section includes a brief description of tasks associated within DOE-EM focus areas, current automation technology and a discussion of how an applicable modular automation system can be applied to DOE operations. The approximate requirements are summarized in Figure 3-2.

#### **3.1 Decontamination & Dismantlement (D&D)**

The amount of decontamination and dismantlement of DOE facilities which will need to be performed via robotics in the next several decades is massive. Some 7000 contaminated buildings will be deactivated and 700 contaminated buildings will be decommissioned. D&D is responsible for decontaminating the contents of these facilities and disposing of 180,000 metric tons of scrap metal.[D&D Focus Area] These operations address the needs associated with the deactivation and decommissioning of nuclear reactors, “hot” equipment such as gloveboxes and machine tools, weapons production facilities, and raw fissile material refinement plants. Such D&D tasks will often need to be carried out on-site across the DOE complex.

Given the wide range of operations covered by D&D activities, there is no one set of manipulator specifications which can address all needs. D&D operations are, in general, the least structured or ordered of the operations within DOE remediation needs. General operational requirements for many dismantlement tasks include the use of modified hand tools (human scale) for cutting, separating, holding, etc. In many cases, a portion of structure must be held in place or supported as another manipulator cuts it free. These parts must then be transferred to a container for appropriate disposal. In decontamination tasks, swipes may need to be applied to the inner surfaces of contaminated vessels or boxes. In some instances, loose items may need to be removed from within confined areas. Some remote operations must even be carried out in pools of water.[Meservey] In short, many of these operations are unique tasks not readily given to conventional automation, however, because of the inherent hazards of D&D environments, remote operations are necessary.

Many challenges to automation exist within D&D operations. The hazardous work environment (shock loads, vibrations, harsh chemicals, radiation, fine particulates, fluids) quickly leads to the failure of even the most rugged system. Developments in advanced tele-operation, needed for most tasks, are just beginning to make real-time force feedback control of robots practical. Previous efforts in remote tele-operation have demonstrated that system operators have a propensity for “abusing” the manipulators in use while carrying out tasks. [Haley] Remote operations require either long umbilical cords, which are prone to damage, or remote power and communications systems, which require greater maintenance. Repair of these systems is often difficult due to contaminated components which are not quickly and easily serviceable. Confined space and portability/mobility issues greatly limit the size of robotic solutions. Additionally, the need for coordinated, dual-arm operation requires advanced criteria-based control schemes which are only now being developed by university research groups.[Sandia]

Specifications for a D&D manipulator for human scale tasks (i.e., human tools and payload) place its maximum continuous load around 880 N (200 lb<sub>f</sub>) in multiple directions. This strength requires the manipulator system to maintain task control under large peak disturbance forces, while permitting a single manipulator to move pieces of material from point to point. A

reach of approximately 1.5 m (59") allows a pair of manipulators set upon a common frame to reach across a large (3 m) work area without repositioning their support. The accuracy required of this type of manipulator is quite low because the user is responsible for closing the loop with camera feedback. However, should advances in real-time environmental modeling permit some autonomous activity, the manipulator would need to be capable of industrial grade positional specifications. Joint-level force control will allow the system controller to enact the most effective control over the forces at the end-effector. Additional high-level control schemes, such as obstacle avoidance and compliance control, will greatly enhance the usability of the system.

The current robotic technology in D&D consists of hydraulic manipulators which are available from two primarily manufacturers: Kraft and Schilling. These hydraulic devices have payloads of around 60 - 100 kg (143 - 220 lb<sub>m</sub>) and reaches of 1.5 - 2 m (60 - 79 in). As supplied from the manufacturer, these systems typically include a simple rate control slave (manual controller with identical kinematics to manipulator) control tele-operation system rather than a force-feedback, computer controlled, sensor assisted system. Research labs have adapted more advanced tele-operation controls to these manipulators, but it is not believed these systems are commercially available for production operation. Hydraulic manipulators possess several advantages and disadvantages. Highly power dense 2.1 MPa (3000 psi) hydraulic fluid combined with remote location of the power generation unit results in a force to weight ratio which is difficult to match with even slower electric manipulators. The manipulators described above weigh approximately 55-100 kg (121 - 221 lb<sub>m</sub>) and thus their payload/mass ratio is approximately 1:1. Commercially available industrial electric manipulators such as the Kawasaki UX100 with payloads of 100 kg (221 lb<sub>m</sub>) have masses of 1400 kg (3087 lb<sub>m</sub>) resulting in a payload/mass ratio of 1:14. Additionally, no known commercially available industrial, electric manipulator is available from its manufacturer with any type of tele-operation control system. Where high payload/weight ratios are not important, the disadvantages of the hydraulic systems often outweigh its benefits as evidenced by the almost complete dominance of electric manipulators in manufacturing facilities. The primary problems are a result of the maintenance associated with hydraulics and the potential leakage of hydraulic fluid. In many industrial settings, contamination of product (food for example) with hydraulic fluid is un-acceptable. In D&D applications fluid leakage results in additional low-medium level waste and it acts as a transport mechanism for other contaminated particles. Hydraulic manipulators are almost exclusively driven by linear pistons. This results in a limited workspace which is highly non-linear. This, along with hydraulic valves and lines, complicates the job of advanced control schemes often needed for the application. Additionally, while the manipulator itself may be lightweight, the overall system portability is low due to the bulky hydraulic umbilical and pump. Finally, as with monolithic electric manipulator systems, these machines are difficult to repair and maintain, particularly within confined, contaminated quarters, such as a glovebox environment.

### **3.2 Chemical Analysis and Automation (CAA)**

Formerly known as Contaminant Analysis and Automation, the goal of this system is to drastically reduce the time and cost associated with manually characterizing millions of samples during the DOE's remediation efforts. [DOE/EM-0297] The Hanford site alone predicts the number of low-level radioactive samples will increase from 50,000/yr. to 1,100,000/yr. by the year 2003. Medium and high-level will increase from virtually zero to over 400,000/yr. [Hollen and

Rzeszutko, 1997]. Based upon results from initial prototype systems, estimates are that costs could be reduced by 30-50% and turn-around times reduced from 30 days to 24-48 hours. [CAA]

To accommodate the wide variety of analyses which must be performed, the designers of the CAA system have adopted a modular approach to both hardware and software using building blocks known as Standard Laboratory Modules (SLM)<sup>1</sup> which comprise the overall Standard Analysis Method (SAM) architecture. Efforts began in 1990. “By combining logically similar functions in an SLM, robotic conveyance is minimized ...” [Hollen and Rzeszutko, 1997]. Thus, it appears that the design, which has been selected, relies more heavily on hard automation rather than sophisticated generic serial robotic manipulators. This approach has been taken for several reasons. One is to permit SLMs to be utilized in a stand-alone manner. Material transfer between SLMs may be either manual or automated, providing flexibility with regard to total system complexity and cost. Within this framework, there are two candidate applications for the products/technology being developed by ARM Automation: 1) Sample transfer between SLMs and 2) Actuation of the hard automation. The prototype system utilized an Hewlett-Packard ORCA robot mounted on a linear track. [Hewlett-Packard] A system of this type is very similar to that which is being developed for Plutonium glovebox operations (indeed some CAA systems may be contained within gloveboxes) and could easily be built from actuator modules. Approximate requirements are summarized in Figure 3-2. For the actuation of the hard automation, intelligent motors can be installed in place of the standard NEMA frame motor/amplifier/motion controller combination and controlled over the same bus as the manipulator. Thus, the entire motion control system would be controlled from a single open-architecture PC-based system controller resulting in reduced wiring, higher reliability and simplified maintenance.

While the above automation system built around DISC™ based modules will offer significant advantages over the hard automation/ORCA combination. Further improvement may be possible by considering a architecture which leverages the flexibility offered by the modular approach. Without additional analysis, beyond the scope of this report, it is difficult to predict if such an architecture exists or what its design would be, but one seems likely, once the limitations of previously available equipment, such as the ORCA robot, are removed. The designers of the Generic Material Handling System (GMHS) utilized in the prototype have imagined such a system as a future CAA development. [Min, 1995] In this system the robot is moved from the table top to an overhead gantry, making precious table top space available for installation of additional SLMs.

No matter what approach, if any, is selected for future CAA systems, the architecture of automation being deployed should be as flexible and modular as the test systems themselves. The plug-and-play characteristics of modular automation would accommodate customization and reconfiguration of new tests. Pending continued funding, simplicity, flexibility and reduced implementation costs will permit the extension of CAA systems for a much wider variety of analysis tasks. [OST 0277]

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<sup>1</sup>™ Standard Laboratory Module and SLM are trademarks of SciBus Analytical Inc. [SciBus]

### **3.3 Mixed Waste Operations (MWO)**

It is estimated that over the next 30 years, the U.S. Department of Energy mixed waste workload will include inspecting, unpacking, sorting, and repackaging close to a million cubic meters of low level contaminated waste material.[EM Data Base Report] [DOE/EM-0127P] These materials and associated contaminants vary greatly from site to site. They may include heavy metals, corrosive liquids or other hazardous materials. Solids may include clothing, tools, wipes, aerosol canisters, bricks, or almost any exposed material which may have become waste during actinide processing. Thus far, efforts have been directed at the non-invasive characterization of the contents of mixed waste barrels, boxes and bins. Following available content characterization operations, some materials must be sorted, verified or separated prior to disposition.[Wadsworth]

The principal tasks surrounding sorting operations include: 1) container transport, 2) container opening, 3) content extraction, 4) offending item isolation and 5) repackaging. The proposed use of automation to accomplish these tasks will require multiple tools of very different characteristics. One large payload “robot” will likely handle large containers from airlocks to a station dedicated to opening such devices. This may be accomplished by a dedicated tool (such as an overgrown can opener) or a manipulator equipped with a general purpose cutting tool. Individual removal of items from the smaller (<1 m (39.4 in) deep) containers will require a mixture of autonomous and teleoperated control. Additionally, some form of force control may be necessary to augment operations. Once picked through or separated, some individual items must be carried to specified storage containers and deposited. The location of these new containers may be far from the original and can require another form of long transport device such as a conveyor or manipulator on a track. [Wadsworth]

Several technical challenges present themselves within these operations. As with most automated hazardous material handling applications, access for reconfiguration and repair are quite constrained in the interest of containment and safety. [INEL] When necessary, human intervention with robotic equipment are limited by time, tools, access and worker payload. While radiation in this environment is considered to be “low level”, its presence along with other harsh substances can have highly detrimental effects on conventional industrial equipment.[McKee] Additionally, the lack of structure within the waste stream calls for a mixture of teleoperation and autonomous control. This presents another challenge to automation, both with and without force control, due to the lack of proven technology available to the user.[Haley]

Based on available task information and prior research in this area, approximate requirements may be determined for the robotic sorting/separating system. A full 6-DOF manipulator would be needed to readily reach and grasp unordered material. A reach of at least 1 m (39 in) would be required if this device is to retrieve materials from the bottom of 55 gallon drums. A maximum payload of 90 kg (200 lb<sub>m</sub>) would suffice for the vast majority of items. These tasks do not necessitate high speed or high accuracy, therefore, a manipulator of “standard” industrial specifications would suffice. Some form of force feedback from either joints or end-effector may be desirable to augment human tele-operation or to maintain “safe” operation while sorting. The control structure will most likely be a combination of automatic and tele-operated tasks. By mounting the manipulator on a linear rail, the same manipulator can then be used to transport the separated items to one of multiple containers located away from the old container and sorting area. Otherwise, the offending item will need to be transferred to another system, such as a system of conveyors or another manipulator for repackaging.[Wadsworth]

Among the most demanding specifications, for the systems currently being envisioned, are its reliability and serviceability. These factors not only ultimately determine process up-time or throughput, but also dictate the amount of exposure to personnel, operating cost, engineering workarounds and secondary waste generation. In order to minimize service and/or repair in-situ, all components with a potential for failure through general use or abuse should be quickly and easily interchangeable.[Haley] Ideally, human portable modules or modules which can be interchanged via a secondary robot will provide the ultimate in reconfigurability and reparability for mixed waste sorting, separation and repackaging.

Research into MWO automation has taken place at both INEEL and Lawrence Livermore Labs. This includes explorations of automated identification techniques, materials transfer, drum opening and container transport.[LLNL] Thus far, no satisfactory solution for MWO automation has been developed. However, ongoing work at INEEL will continue to pursue viable solutions for automation in this area.

### **3.4 Tanks**

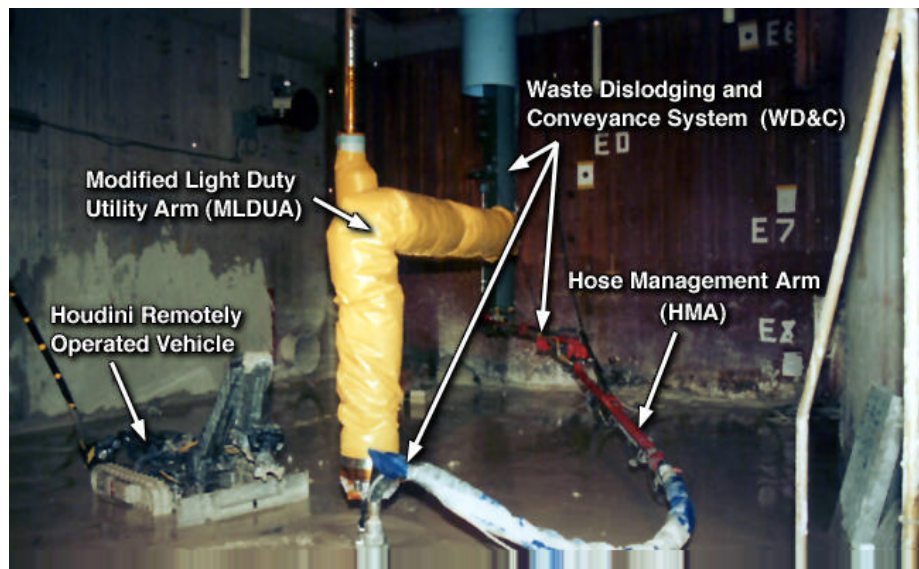
The associated tanks at the U.S. Department of Energy's tank farm facilities located at ORNL, Hanford, INEEL, and SRS were built to collect, neutralize, store and transfer the liquid and slurry portion of radioactive and/or hazardous chemical wastes. These tank farms were constructed between 1943 and the mid 1980's with capacities ranging from 13,000 to over 1,000,000 gallons. Today, these tanks contain varying amounts of liquids, solids and sludges. This material is composed of organics, heavy metals, and various radionuclides including transuranic materials.

Many factors significantly complicate the remediation of these tank systems, including the high concentration of radionuclides involved, the location of the tanks below ground, and the complexity of governing regulations. Matters are complicated and hurried as these tanks reach the end of their design life and begin to leak into the environment. The waste contained in these tanks is referred to as mixed or mixed-transuranic waste and must be handled in accordance with appropriate regulations for such categories of waste. Additional complications stem from the concentration of radionuclides in sludges and solids which is sufficiently high to require that remotely-operated systems handle material in the interest of worker safety.

An advanced waste removal technique, called confined sluicing has been developed for tank waste removal. Confined sluicing will utilize a variable pressure cutting jet to loosen the tank sludge and a water jet pump to remove the sludge and liquids from the tanks. The confined sluicing equipment will be moved around inside the tanks with a robotic arm and/or vehicle. A light duty, long reach manipulator was developed by Spar for this application through the Tank Focus Area. Spar's arm, the Light Duty Utility Arm (LDUA) shown in Figure 3-1, is a remotely controlled manipulator designed for use in extreme environments common in the underground storage tanks. The LDUA system provides a mobile, multi-axis positioning system that accesses the tanks through existing openings in the tank dome. The LDUA system is used for inspection, waste characterization and tank mapping. In addition to LDUA, a tracked vehicle with a robotic arm called Houdini was developed by Redzone for dislodging the sludge which resides on the bottom of the tanks after LDUA has removed liquids. At this time, LDUA and Houdini are still being evaluated as potential solutions for tank farm remediation.

The extremely long reach of this application (greater than 13') coupled with the need for deployment through a 10" access port makes this a difficult task to approach with the scope of

actuators currently envisioned for deployment. Given that an acceptable solution may well exist in LUDA, the application of ARM Automation's modular robotics to tank sludging remediation is not deemed necessary at the present. However, should specific needs arise which are more well suited to the scale of ARM Automation technology, these can be pursued.



**Figure 3-1 - The Houdini vehicle (left) LUDA (right)**

### **3.5 Overview of Manipulator Requirements**

Based upon the review of each DOE automation application, a set of approximate manipulator specifications has been developed and is summarized in Figure 3-2. Some general comments on the specifications are as follows: A key factor in selecting the accuracy and repeatability specifications is operation mode. Tele-operated systems are the least demanding because of the adaptability of the human operator. Teach-pendant taught systems do not require much accuracy, but demand repeatability to ensure points need not be retaught (a tedious process). The most demanding are off-line programmed, CAD driven systems, which assume a perfect world model. Both accuracy and repeatability are required for these systems. Unlike some high-volume, industrial production systems, speed is not critical for any of the DOE applications considered, thus, the speed specification serves merely as a guideline. Tank applications have not been included because they are the least conducive to the modular approach, and are sufficiently unique to be addressed by existing monolithic designs.

	APP	D&D	CAA	MWO
<b>Manipulator Specifications</b>				
Reach [m (in)]	0.6 (24) to 0.8 (32)	1.5 (59)	0.6 (24)	1 (39)
Payload [kg (lb <sub>m</sub> )]	8 (18) to 10 (22)	90 (198)	0.5 (1.1) to 2 (4.4)	90 (198)
Arm Degrees of Freedom	4 to 6	6 x 2 arms	4 to 6	6
Tele-operated, Teach-pendant Playback, Off-line	Initially teach-pendant Tele and off-line poss.	Tele-operated	Teach-pendant.	Primarily Tele-operated
Accuracy / Repeatability +/- [mm (in)]	1 (0.040) 0.1 (0.004)	N/A 0.5 (0.020)	0.5 (0.020) 0.25 (0.010)	N/A 0.25 (0.01)
Linear Rail Mount	For some tasks	Not typically	Yes	Likely
Speed [m/sec (in/sec)]	0.7 (28)	0.91 (36)	0.7 (28)	0.91 (36)
Force Control	No	Yes	No	Yes
End Effector Type	Electric gripper	Mix of electric (110VAC) and pneumatic	Standard gripper (electric or air)	Multiple tools (electric or air)
Portability	Pieces must facilitate bagout	Yes	No	System must facilitate "hot" repairs
Obstacle Avoidance	Yes, or limited motion	Yes (for autonomy)	No, highly structured environment	Advantageous (not needed)
Positive Pressurization	Yes	Not typically	Not typically	Yes
<b>Operational Conditions</b>				
Radiation Level [rad/h]	0.3-1	0.1-1000's	None at present, Potential exists	0.001-0.01
Corrosive/ Haz. Environment	Yes, Plutonium dust	Yes	None	Mix of industrial chemicals
Confined Space	Yes	Yes	Yes	Slightly
Serviceability	Through glove ports	Suited technicians	Suited technicians	Suited technicians
Wet or Spray	No	Potentially (even submerged)	No	Potential from cutting system

**Figure 3-2 - Overview of DOE Manipulator Requirements**

## **4. Automated Plutonium Processing**

Automated Plutonium Processing (APP) primarily consists of material handling operations which take place both inside and outside radioactively “hot” gloveboxes. Applications exist within Environmental Management (EM), Materials Disposition (MD) and Defense Programs (DP). There are many types of Plutonium processing operations performed within the DOE complex, however, some are classified and, hence, it was not possible to obtain their requirements in detail. As an example, the quantity of nuclear material residue which must be processed and separated, while substantial, is classified. Thus, due to relative abundance of publicly available information, the following sections contain the most information on operations related to the need to process the approximately 38.2 Metric tons of Plutonium which has been declared “excess” due to issues related with the end of the cold war [Pu Excess].

### **4.1 Plutonium Processing Characteristics and General Automation Needs**

Plutonium processing is addressed here in five main categories:

- (1) In-box processing and stabilization of residues and segregation of Plutonium laden materials. Processes include chemical and thermal processing, material analysis and packaging. This application area is young relative to the others, but it will increase in importance over the next several years as decontamination and decommissioning of the facilities (often gloveboxes) which store the materials accelerates.
- (2) Processing of Plutonium metal and oxides within gloveboxes for weapons production or disposition. These operations incorporate complex machinery such as lathes, furnaces, etc. Containers up to 10 kg (22.05 lb<sub>m</sub>) are most commonly used.
- (3) Handling and inspection of containers of Plutonium and/or Plutonium Oxide both before and after glovebox operations. These containers are either clean or have been decontaminated and thus may be handled outside of the gloveboxes.
- (4) Assembly and disassembly of weapon mechanical, electrical, explosive and fissile components.
- (5) Handling, inspection and transfer of larger containers used to transport Plutonium between and within medium and long term storage facilities. An example is the Stage Right project at Pantex which utilizes an automated forklift for storage and retrieval of large containers stored on pallets. [Stage Right] Containers in this system are 113.6 L (30 gallons) in size.

While all of these operations involve exposure to radiation and hazardous material, the glovebox operations of Category (1) and (2) most readily justify and require the application of automation. The tasks in Category (1) are a super-set of the tasks in Category (2). Many of the details of the operations required for Category (1) are yet to be developed and thus a versatile automation system is called for. Category (2) tasks are structured and thus are good initial candidates an APP implementation. While the bulk of Section 4 will expand upon these areas, a few words will be mentioned on the needs of Categories (3) - (5) and the applicability of modular automation to them.

The tasks in category (3) are the most structured of the Plutonium processing tasks discussed. Clean containers of a limited number of standard sizes and geometries are transferred between processing stations. Payload requirements are heavier than those for Category (2) and lighter than those for Category (5). Work envelope requirements are larger than those required within the glovebox. Either gantry or fixed base manipulators with 2-6 DOF and payloads of at least 10kg (22 lb<sub>m</sub>) are required. A modular automation system is suited to this task. Depending upon configuration, reach and payload requirements, one or more additional module designs will be required. These systems can be controlled over the same bus and system controller as the glovebox systems thus offering the design, service and operational benefits of the modular approach discussed in more detail in other documentation. [ARM ROA Proposal]

Given the classified nature, the least information is available for the requirements of Category (4) but some informed assumptions are made herein. Automated assembly of new weapons designed for automation is feasible. Automated disassembly of weapons (which may not have been designed for any type of disassembly, never mind automated) is not likely to be practical. It is speculated that the manufacture of new weapons will have automation requirements similar to complex consumer and industrial products, thus a modular approach can be feasible. Given the lack of information on the actual application, it is difficult to predict which types and sizes of actuator modules will be required.

Handling of the containers in Category (5) requires large payloads and work envelopes best served by mobile platforms of the type already developed. From the literature reviewed, there does not appear to be a need for additional automation or robotics in the handling operations. There may be a need for a manipulator mounted on a mobile platform for the placement and movement of sensors around and within the drums and pallets for the ongoing inspection tasks. This manipulator would most likely be a simple device (3-4 DOF) with a moderate reach (1 m (40 in)), light payload (3 kg (6.62 lb<sub>m</sub>)) and moderate positional repeatability (0.5 mm (0.020 in)). Exact specifications would be determined by sensor characteristics. Manipulators of this type could be easily built using a modular approach. One larger actuator design in addition that those currently being developed may be required.

## **4.2 Plutonium Glovebox Automation System Challenges**

As Section 4.4 alludes, operations in glovebox Plutonium processing are similar to many industrial tasks, but the unique environment and material create the following unique set of challenges [McKee] :

- 1 Plutonium
  - 1.1 Low to moderate levels of ionizing radiation.
  - 1.2 Highly abrasive.
  - 1.3 Corrosive.
  - 1.4 Pyrophoric.
  - 1.5 Disperses and permeates readily. Diffuses quickly.
  - 1.6 Reaction and behavior with equipment is not well understood.
- 2 Glovebox Environment
  - 2.1 Existing gloveboxes may not be readily altered or even modified at all.
  - 2.2 Complex mechanical operations for maintenance and repair are difficult or impossible through gloves.

- 2.3 Failed equipment may not be removed easily or at all. If a broken piece of equipment cannot be bagged-out through a glove port (approximately 8½" in diameter) it must remain in place. 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. A moderate sized glovebox alone costs between \$250,000 and \$500,000.
- 2.4 An equipment malfunction which penetrates the glovebox and exposes the room to Plutonium is catastrophic. In addition to the human exposure issues, cleanup can easily run into the millions of dollars.

### **4.3 Approaches to Glovebox Plutonium Handling**

There are two extremes to the design of any automation system:

- 1) Design the process and tools such that "simple" automation may be applied. This may be either dedicated "hard" automation if high speeds and volumes are required or standard robotic manipulators.
- 2) Perform the process exactly as would be done by humans with "complex," highly flexible robotic systems. This may mean force-feedback tele-operation, off-line programming, automatic environment modeling, redundant manipulators and other advanced technologies.

Depending upon the application, the optimal solution often lies somewhere in between. While many factors are involved in the selection of the ideal system design along this continuum, one key factor is the degree of flexibility required. For example, D&D operations clearly land near the high end with a mandatory requirement for sophisticated features such as tele-operation, sensor feedback, etc. An example at the other extreme is the assembly of the three plastic pieces which comprise a Compact Disc (CD) case. As a general rule, there must be a compelling reason to select a complex automation system over a simple one, given the higher cost, risk and lower reliability which such systems inevitably entail. While the lack of structure in many DOE tasks calls for manual operations, radiation and hazard levels discourage or preclude the use of any human labor.

APP applications land in a band somewhere in the middle of the two extremes. Installations into existing gloveboxes obviously must have high flexibility since they must work with the tools and equipment originally designed for human operators. For these applications, ARM Automation proposes a six (6) DOF manipulator on a linear track mounted to the ceiling of the glovebox. This configuration creates the least interference with the existing equipment while offering the flexibility of tools designed for humans within a work volume which covers the entire glovebox. In contrast to D&D applications, most tasks will still be structured, repetitive operations which may be performed autonomously. This is fortunate given the degree of difficulty and level of skill required to operate a remote system within the confined glovebox environment while looking through the small windows of the glovebox. Nevertheless, many glovebox operations, particularly the "hot" ones, will benefit from some sort of tele-operated control to accommodate off-normal maintenance tasks and new system set-up. This tele-operation interface does not need to be as sophisticated and those for D&D systems which will be used continuously for unstructured tasks. ARM, therefore, proposes the development of simple tele-operation system which does not utilize force-feedback.

Given the liability issues involved with penetrating the glovebox barrier, the most robust system to prevent such an occurrence is desirable. For the structured tasks in new process designs hard joint limits may be desirable. For tasks which require access to the maximum possible work envelope a more sophisticated approach is necessary. Thus, ARM proposes the development of a static collision avoidance system. This system will prevent the manipulator and a modeled tool from being driven into the fixed glovebox shell during manual operation. It will be based upon a CAD generated solid-model of the work-cell. The operator will have responsibility for avoiding collisions with objects within the glovebox not modeled in the CAD model. This includes any moving objects other than the manipulator itself.

#### **4.4 Previously Developed Glovebox Automation Systems**

A review of the literature did not uncover any previously developed modular robotic systems for glovebox (Plutonium or otherwise) operations. However, at least two dedicated glovebox processing systems have been developed.

Lawrence Livermore National Laboratory (LLNL) has had several demonstration glovebox facilities in operation since April of 1991. [Dennison, et al] In August of 1993 LLNL contracted with International Business Machines (IBM) to supply a gantry robot for installation in a Tritium processing glovebox. This large robotic system was installed in a “double-decker” glovebox for handling of large containers. The robot has six degrees-of-freedom; a three revolute axis wrist attached to three linear Cartesian axis gantry system. The robot is able to reach 1.07 m (42 in) down, grasp 68 kg (150 lb<sub>m</sub>) objects, traverse 7.2 m (282 in) in X, 0.69 m (27 in) in Y and 1.5 m (60 in) in Z. Significant space is required above the plane of the X-Y axis to accommodate the Z tower, thus the requirement for “double-decker” gloveboxes. Two television cameras were mounted on the robot for tele-operation. The containers handled are either 55 gallon drums or DOT 7A containers which are made of steel and have dimensions of 2.18 m (86 in) long x 1.17 m (46 in) wide x 1.07 m (42 in) deep. Both autonomous and tele-operated control are specified. According to [Dennison, et al] the system was to be controlled by an IBM Series 2 controller. Initial operation was scheduled for the 2<sup>nd</sup> qtr of 1995 with completion in 1996. From [LLNL2], it appears that further development work has taken place which includes hardening and the addition of an open architecture controller. [IBM] Also indicates that some version of this system was aimed at plutonium glovebox operations. From what literature reviews have revealed, this system does not seem ideally suited to the needs of Plutonium processing for several reasons: (1) The volume and payload are larger than necessary thus requiring larger and more expensive gloveboxes, (2) Linear actuators contain much more sliding contact area and open components which are susceptible to wear from abrasive Plutonium particles, and (3) The system must be constructed and repaired inside a glovebox and the large linear components cannot be bagged out. As a general observation the three axis Cartesian configuration does not seem to be a good choice for any “hot” glovebox operation given the volume required to clear the Z-axis tower. This system may prove reasonable if a double-decker glovebox is already in place or required for other process related reasons.

In approximately March of 1996, the U.S. subsidiary of British Nuclear Fuels, BNFL Inc., was awarded a \$53M contract to supply technology to stabilize and package plutonium at the Rocky Flats. [BNFL] The Rocky Flats Environmental Test Site (RFETS) has a requirement to stabilize and package 6,600 kg (14,553 lb<sub>m</sub>) of Plutonium metal and 3,200 kg (7056 lb<sub>m</sub>) of plutonium compounds. [Rocky Flats] The BNFL system combined a furnace for heat-drying

Plutonium oxides and a packaging system to place the processed material in 50 yr storage containers. This highly automated system places most of the equipment inside the glovebox which created problems highlighted by the following quote "...maintenance crews would be required to enter radiologically controlled areas in the event of system failure." [BNFL2] The system is due for delivery in July, 1998, but only the automated packaging equipment will be utilized. Feeding of the oxides into the stabilizing furnaces will be performed manually in gloveboxes. The original system specifications called for a throughput of two (2) cans every eight (8) hours. An improved design has a target of six (6) cans every eight (8) hours. [BNFL2]

#### **4.5 Advanced Recovery and Integrated Extraction System (ARIES)**

The most visible example of glovebox Plutonium operations is the ARIES project being developed by Los Alamos National Laboratory (LANL) and Lawrence Livermore (LLNL), in partnership with other national labs. ARIES is a system for processing Plutonium pits removed from "excess" nuclear weapons. This system has been designed to operate "dry" greatly minimizing secondary waste generation as compared to traditional processes.

"The goal is to provide designers of future weapons dismantlement and plutonium handling facilities with fully integrated technologies that are inherently safer and produce significantly less radioactive and mixed waste than formerly-used technologies." [ARIES ICS]

As currently designed, the system contains a mix of manual and automated material handling operations. As technology and time permit, automation of additional processes may be considered. An example is the cell being designed by Sandia National Labs (SNL) described in Section 4.6. The ARIES system consists of several gloveboxes which are interconnected via a conveyor system. A different process is performed within each glovebox. The processes are:

1. Pit Bisector
2. Hydride-Dehydride Furnance:
3. Hydrox Furnace
4. Canning
5. Electrodecontamination

To ensure tight control over the amount of Plutonium processed, it is weighed both upon entering and exiting each glovebox. A final step, Non-Destructive Assay (NDA), is performed outside of the gloveboxes. The output of the system is a decontaminated, sealed, multi-wall container containing a known quantity of Plutonium metal or oxide. The resulting material no longer contains classified shape information and is in a form which is more difficult to produce weapons from. When in production, the containers will ultimately proceed to either long-term storage or a Mixed-Oxide fuel (MOX) production facility.

The designers of the automation systems for the production version of the ARIES, or its successors, may have the option to modify the process, tooling and glovebox to simplify the automation tasks. This luxury will reduce the requirement for highly sophisticated, flexible robotic systems. To gain a better understanding of the potential for automation in a line such as ARIES, a simple process analysis which identifies the key actions and tools was performed and the results are summarized in Figure 4-1. The actions fall into two basic classes: material handling and tool operation. With the goal of "getting the most bang for the buck" at the lowest risk, the automation of the material handling tasks makes sense as a first step. This approach takes advantage of the fact that the container sizes are standardized to eliminate the complexity of a

tool changer. The movements are also relatively simple. Further automation will require interaction between the tools and the automation system. As discussed above, two options are available: (1) Operate human tools and (2) Redesign the tools for operation with less complex automation. An example would be the opening and closing of a furnace hood; either a robotic manipulator could open and close it or an actuator could be added to the furnace itself. Decisions such as these will have to be made by the designers/integrators of the specific glovebox automation system. The modular approach provides the flexibility to build a system using either approach or a combination of both.

Actions		Tools
Material Handling:		Scale
Move	Slide	Bisector
Drop	Remove	Hoist
Push	Orient	Stick
Transfer		Can sealing tool
		Can opening tool
Tool Operation:		Oxidation furnace
Open	Seal	"Funnel" tool
Oxidize	Bisect	Welding station
Weigh	Decontaminate	Decontamination chamber

**Figure 4-1 - ARIES Primary Tools and Actions**

#### **4.6 Sandia National Laboratories ARIES Baseline and Demonstration**

Engineers at Sandia National Laboratories (SNL) are designing an automated cell for the ARIES line. It is a rational first step given the challenging environment created during the processing of Plutonium. Their approach appears to match that outlined towards the end of Section 4.3. In this glovebox, SNL is combining two operations: welding and electro-decontamination of the material container. The system utilizes two FANUC LR-Mate robots, whose specifications are shown in Figure 4-2. This robot is traditionally used for part loading operations. While not ideal for the task at hand, it is the best commercially available option. The biggest problem with this manipulator is maintenance and repair within the glovebox. Even a task as simple as removing the cap from the grease zerk fitting becomes nearly impossible with gloves. Very few failures will be repairable inside the glovebox, and hence, the entire LR-Mate is viewed as a disposable unit. This creates significant challenges in several areas: 1) Removal and replacement of the manipulator, 2) Disposal of the failed manipulator and 3) Calibration of the new manipulator. After significant effort, the SNL team has devised a clever system by which a failed LR-Mate may be lowered down through a large portal in the glovebox into a bag and drummed for disposal. This system utilizes a linear guideway system to prevent Plutonium spillage due to the robot tipping over. The resulting operation is elaborate and requires time and care to perform. Despite the novel approach, it still has disadvantages in that it cannot be retrofitted to existing gloveboxes and has yet to be qualified for safety. [McKee]

The SNL system is one of the most developed Plutonium glovebox automation systems discovered in the preparation of this report. Because of its suitability, it is proposed that this site and application be used for field testing and demonstration. A subset of the more flexible linear track/gantry system described above can be tested at SNL, given the optimal requirements of their

design. A four (4) or five (5) DOF subset of the six (6) DOF manipulator above would be used. Assuming a Puma configuration is used, the distal arm roll and possibly the wrist roll actuator would be removed. Furthermore, this approach would test the capability of the modular system to be reconfigured. The tests at ARM's facilities will demonstrate the potential of the flexible system for longer term applications while the tests at SNL will provide a preview of how the modular approach might be first implemented in an early production environment.

Item	Specification				
Degrees of freedom	5				
Payload	3 kg (6.6 lb <sub>m</sub> )				
Payload (reduced speed)	4 kg (8.8 lb <sub>m</sub> )				
Mass	38 kg (85 lb <sub>m</sub> )				
Repeatability	+/- 0.07 mm (0.003 in)				
End Effector Pneumatics	4 standard, 6 optional				
Reach	615 mm (24.2 in)				
Axis Specifications	Motion Range	Speed (°/sec)	Moment (N·m)	Inertia (kg·cm·s <sup>2</sup> )	Brake
1	300°	150	-		Optional
2	180°	150	-		Y
3	135°	180	-		Y
4 (reduced speed)	240°	170 (100)	5.39 (6.86)	1.05 (1.4)	N
5	360°	240	3.92	.41	N

**Figure 4-2 - FANUC LR-Mate Specifications [FANUC]**

## **5. APP Manipulator and Actuator Requirements**

The previous sections have provided an overview of the requirements of the APP task and began to offer some potential solutions which will be implemented during this project. There are two aims to this section: (1) Refine those requirements into a starting point for the design of the manipulator to be built under this project and (2) Begin to map the refined manipulator requirements into high actuator level requirements, particularly those effected by the needs of the other DOE applications.

### **5.1 APP Manipulator Requirements**

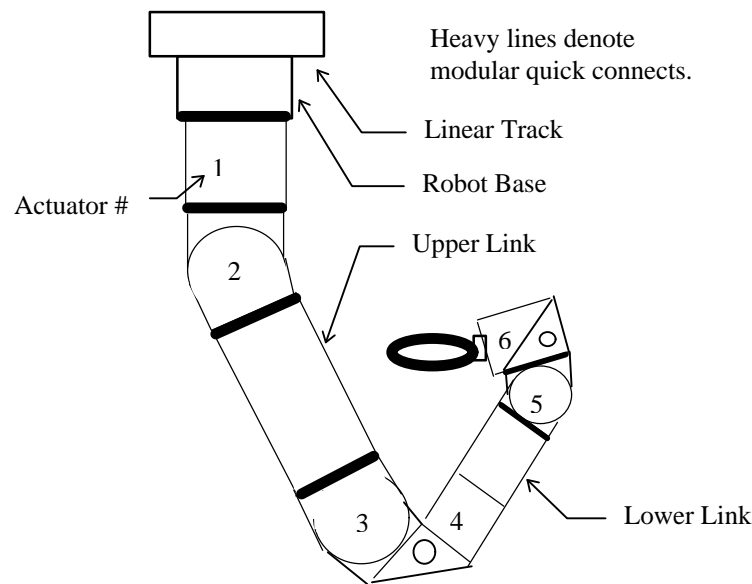
As described in Section 4, two systems have been identified for APP: (1) A flexible, more complex system, which meets the needs of a wide range of APP tasks and (2) One less complicated, which meets the specific requirements of the ARIES automation cell being developed by SNL. The beauty of the modular approach shines as the second system can simply be constructed by removing modular components from the first, and may be configured within a brief amount of time. Thus, it is proposed that the first system be built and demonstrated at ARM's facility and then the second system be tested at SNL. This strategy will test the ability of the modular approach to accommodate system reconfiguration. The following sections describe the requirements and design envisioned for each system. Both systems will be controlled with the same open-architecture PC-based system controller. The specific supplier of the system control software will be selected in Task 1.2.8 outlined in the project's Management Plan.

#### **5.1.1 ARM Demonstration System**

Based upon needs determined in the above Sections, ARM proposes the following for the versatile Plutonium glovebox automation system: A 5-DOF Pitch-Pitch-Roll-Pitch-Roll (PPRPR) manipulator suspended from a linear track mounted to the ceiling of the gantry with the axis of the first pitch actuator parallel to the axis of the linear track. The resulting system will be controlled as a six (6) DOF manipulator. This approach simplifies tele-operation by eliminating the control issues associated with redundant (> six (6) DOF) manipulators. Future systems may use a more traditional (6) DOF manipulator (the above PPRPR with a first Roll joint added) on the linear track. In this configuration the track could be treated as an indexer which places the robot into position or as a redundant manipulator if required. The later option is unlikely for APP applications, but it may be desirable to reduce the length of the linear track for bag-out procedures. (Adding the first roll joint permits the manipulator to swing out off the end of the track, thereby reducing the track length, but access to the corners is sacrificed.) The target reach will be 40" with a 10 kg payload. The linear track will have a travel of approximately 1 m (39.4 in).

The most complex system anticipated will be used for the dynamic simulation to ensure the actuators are sized appropriately. This is a 6-DOF suspended from a track are specified as follows: Joints 1,2 and 3 are large actuators and 4,5 and 6 are small. Each modular interface (shown in black) is 1" in thickness. The configuration is R-P-P-R-P-R. The manipulator will be suspended from the centerline of the glovebox on a linear track which is 4 inches thick (vertically) and 8 inches wide. The useful length of track will run up to within 6 inches of each end of the box. Measuring from the ceiling down, the axis of joint 2 will be 12" below the ceiling. Axes 1 and 2 intersect and are perpendicular. From the center of joint 2 to the center of joint 3 (parallel

to 2) is a distance of 20". Axis 4 is offset from the axis 3 (by  $\frac{1}{2}$  the diameter of joint 3 + 0.5" for the yoke + 1" for the modular interface +  $\frac{1}{2}$  the diameter of the smaller actuator). The base of actuator 4 is tangent to the diameter of pitch actuator 3. There is a distance of 18" along the center of the lower link (axis 4) between the projection of pitch axis 3 and pitch 5. Pitch 5 intersects with axis 4. Like the elbow, roll axis 6 is offset from axis 5 (by  $\frac{1}{2}$  the diameter of joint 5 + .35" for the clearance of the yoke + 1" for the quick connect +  $\frac{1}{2}$  the diameter of the smaller actuator). As shown in the figure, the base of actuator 6 is tangent to the diameter of pitch 5. The end effector tool is yet to be identified and will simply protrude from the tool plate of actuator 6.



**Figure 5-1 - 6-DOF Suspended from Track**

#### 5.1.1.1 Tele-Operation

ARM's sub-contractor, The University of Texas at Austin will be the lead on the activities of Sections 5.1.1.1 and 5.1.1.2. A simple tele-operation system will be developed which will permit the glovebox operators to perform occasional off-normal tasks such as maintenance. This system will be a subset of the UT's OSCAR architecture, and will form the foundation upon which the more advanced tele-operations systems required for D&D and MWO operations will be built. No force-feedback will be used. UT will select an architecture and controller consistent with the above. ARM envisions a rate control system which operates the manipulator in end-effector space. All software will be developed for and integrated with the open-architecture system controller.

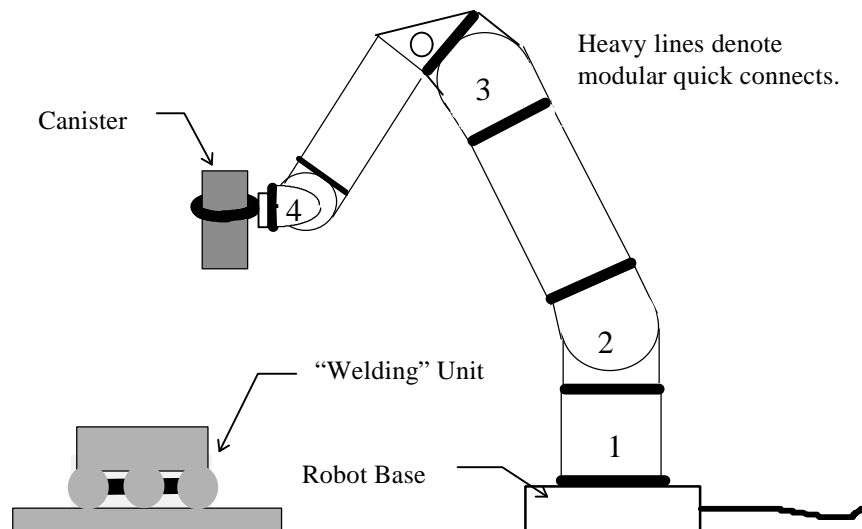
#### 5.1.1.2 Collision Avoidance

There will be applications which require access to the entire robot work envelope thus making hard joint limits unfeasible. To reconcile this need with the risk of penetrating the glovebox, UT will develop a static collision avoidance system. This system will prevent the

manipulator, its end effector and payload from colliding with the glovebox. The glovebox model will be a simple CAD generated solid model representation. Objects inside the gloveboxes will not necessarily be modeled and thus the operator may be responsible for avoiding collision with these objects within the glovebox. The system will provide the operator with feedback (either audible, visual or both) as they approach a keep-out boundary, a defined distance away from any glovebox surface. The allowed speed will be reduced as the manipulator approaches the keep-out boundary, at which point the manipulator cannot be driven past the boundary. It will retain freedom of motion in directions which do not penetrate the boundary, making it easy to drive the manipulator away from the boundary.

### 5.1.2 SNL Demonstration System

The requirements of the SNL demonstration are among the least demanding of any of the systems evaluated. The end-effector may be either pneumatic or electric within a range of voltages. Only on/off control of the voltage or pneumatic supply is necessary. Ideally, the payload should be 10 kg (22 lb<sub>m</sub>) with an absolute minimum of 5 kg (11 lb<sub>m</sub>). To prevent wear due to Plutonium particles, as many of the joints as possible should be positively pressurized. This pressure line may initially need be external to the manipulator. At present, it is believed that four (4) DOF are sufficient for this task. A RPPP configuration which is a subset of the PPRPR configuration (described above) with the last two roll joints removed and a first roll joint added. (see Figure 5-2)



**Figure 5-2 - 4-DOF Robot for Upright Canister Transfer**

The most unique requirement of this system stems from the fact that the system is teach pendant taught and cannot be easily re-taught once installed in the glovebox. As a result, the manipulator must be repeatable after module replacement or manipulator re-assembly. This mode of operation may require a generic manipulator calibration scheme.

## 5.2 Actuator and End-Effector Interface Requirements

Due to the versatility of the modular approach, requirements of the other DOE tasks force little compromise in the specifications for the APP manipulator design, but careful thought must be given to the actuator level decisions. There are two classes of decisions which must be made with regard to the actuator designs introduced. The first decision determines which actuator sizes from the available spectrum are appropriate for this manipulator system. The second class of decisions determines actuator level performance and design specifications.

With regard to the actuator spectrum, it will not be desirable to design both modules with very similar capacities even if that is sufficient for APP. To ensure a maximum of versatility with the initial two designs, they should be spaced as to maximize their usability in other applications without being severely oversized for the APP task. For example, this could result in a first joint which has excess capacity for the APP application. These architectural decisions will be made as the modules reach final design and the APP actuator torque requirements are determined through simulation. Additionally, strategic decisions must be made with regard to design features which shall effect the cost, design time, and applicability of these devices to APP applications, other DOE applications and industry.

Actuator Property	“Small”	“Large”
Mass (kg)	2.5	6
Diameter (m)	0.095	0.130
Length (m)	0.105	0.150
Gear Ratio	100:1	100:1
Input Side Inertia (kg-m <sup>2</sup> )	4.38X10(-5)	2.73X10(-4)

**Figure 5-3 - Preliminary Specifications for APP Actuators**

Some of the more significant decisions which will be made during the design process will now be described. This design will pass the wire internally through the links and actuators with connectors integrated into a single electro-mechanical interface. While difficult to achieve, this approach results in a clean, robust design which can be quickly and easily reconfigured. Feasibility demands that the number and size of wires be kept to minimum due to space requirements. In addition to volume, the number of wires also has a critical interrelationship on the degrees of rotation required. If continuous rotation is required, slip ring channels must be minimized to reduce size and cost. While not required for APP, a decision to include pass through 110 VAC power for operation of end-effectors, such as in D&D applications, will add to the complexity of this design task. This feature will be incorporated unless it generates extreme design compromises.

Pass-through pneumatics has an even greater impact on the design. Providing a pressurized passage through the actuator and a pneumatic interface will add a significant amount of complexity. Unfortunately, many system integrators are very comfortable designing pneumatic end-effectors and may not have the skills or interest to develop electric designs. In addition, electric end effectors are inevitably larger than their pneumatic counterparts, thereby, reducing effective payload. Again, while not required for APP, if a clever way can be found to achieve a pneumatic pass-through without adding significant complexity, one will be incorporated.

The last major architectural decision involves joint-level torque sensing. Some roboticists prefer to resolve end-effector force/torque load measurement based upon joint level torque

measurements for force-controlled tele-operated systems. This approach is only practical on six (6) DOF systems and thus the use of an end-effector mounted six (6) DOF load cell is preferable and more versatile. Joint torque sensing also allows a system to operate in a more precise torque mode. Currently, it is not believed that feature is worth the cost and complexity for any of the DOE applications, and thus will not be incorporated in these designs. Other requirements, such as positional accuracy and sensor resolution, will be specified as designs mature to insure a maximum of versatility across all actuator applications.

A final requirement arose during the kick-off meeting. The designs envisioned to date incorporate a finned housing to facilitate heat-transfer. It was observed that any non-smooth surface, such as fins, complicates decontamination and should be avoided if possible. A final decision will be dependent upon heat transfer and load calculations, but smooth surfaces will be incorporated wherever possible. Given the more favorable surface area/volume ratio of the smaller actuator smooth surfaces are more likely on this design.

## 6. Conclusions and Recommendations

After a review of applications within DOE-EM focus areas and available modular robotic automation technology, it has been determined that no existing robotic systems present a feasible solution to these tasks. While previous designs of modular manipulator systems have demonstrated valuable design concepts, each implementation of the base technologies has proven insufficient to meet the requirements of industry (and consequently EM tasks) for reasons of performance, size, deployability or net cost. For this reason, a new robotic technology is under development by ARM Automation which can not only meet the technical requirements of robotic systems, but can also provide a timely, cost effective solution to EM robotic automation needs.

Data gathered from DOE sites and personnel familiar with these operations has provided ARM Automation with a fundamental understanding of the needs for robotic automation in EM applications and the conditions under which it must operate. A set of general manipulator and system performance requirements have been defined for each application class. From these high-level requirements, ARM Automation may plan its architecture and product to best accommodate these needs.

As expected, DOE applications other than APP have the most demanding requirements and must be considered at this point to ensure the applicability of the actuators developed beyond APP. The major issues revolved around the requirements of tele-operation and include joint-level torque sensing for force feedback operation and high tip speeds. The second issue will be addressed by incorporating a position sensor with a greater dynamic range thus allowing higher joint speeds. The first will not be addressed under this project given the complexity involved. However, a path forward will be preserved through careful design of the electronics and mechanical components to permit the addition of torque sensing in future designs.

The requirements of APP glovebox operations, have been examined in detail and it is clear that it is an ideal initial area of deployment for ARM's modular actuator technology. The recommended approach is twofold. First, ARM will develop two actuator sizes suited to create a 6 degree-of-freedom manipulator on a linear track. This implementation of ARM's actuator modules will be suitable to meet the most comprehensive glovebox automation tasks. This system will be constructed and tested at ARM's facilities for use with a manual controller. Secondly, a specific task was identified for system demonstration inside a glovebox. This Plutonium container transfer operation, being implemented by Sandia Laboratories, would serve as an excellent application for demonstrating the advantages of the proposed modular robotic system and is recommended as an initial point of deployment. The twofold approach allows ARM to demonstrate the flexibility of its modular technology and to deploy a system which is no more complex than the task demands. From these initial system demonstrations, it will then be possible to immediately deploy more complex systems into APP applications as well as other areas.

By leveraging the development underway, the robotic automation efforts of other EM operations can also benefit. By sharing this common, flexible machine architecture across multiple areas while utilizing open control and communications systems, net costs and system deployment timelines can be reduced. Therefore, it is recommended that DOE problem holders take advantage of this opportunity to evaluate existing and planned robotic applications with the proposed technology in mind.

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