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***ROBOTICS TECHNOLOGY
ASSESSMENT FOR
DECONTAMINATION AND
DISMANTLEMENT TASKS***

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Abstract

As the name implies, D&D tasks focus on facility decontamination and dismantlement operations. In order to conduct those tasks, characterization of facilities and their surveillance are carried out also by the D&D group, as well as the packaging and removal of items after the dismantlement process. These tasks are characterized by their diversity and demanding nature. Because of the large size of facilities and equipment, dimension of the robotic system used in this application will be comparable in size to mobile cranes. This constraint alone eliminates most of the existing robots, but some hydraulically-driven ones. After reviewing D&D task requirements, we look at the state of the art in current robotics technology. Pointing out certain commercial robots and remote manual controllers for possible use in these applications, we assess the current status of component technologies in robotics. This shortly discusses the strength and weaknesses in each area. Under the guidance of these assessments, we recommend specific robotic systems for D&D operations, and then conclude by noting the areas that need further development.

1. Introduction

DOE's Robotics Technology Development Program focuses its research and development efforts in five major areas mainly to address the diverse needs of DOE's Environmental Restoration and Waste Management (EM) Program. These programs are

- Robotics Tank Waste Retrieval (TWR)
- Robotics Contaminant Analysis Automation (CAA)
- Robotics Mixed Waste Operations (MWO)
- Robotics Decontamination and Dismantlement (D&D)
- Robotics Cross Cutting and Advanced Technology (CC&AT)

Although each of these programs produces results towards various EM needs, in this paper, we specifically concentrate on the Decontamination and Dismantlement (D&D) tasks and their robotics needs.

The D&D group aims to automate the entire decontamination and dismantlement process; thus, it is one of the most ambitious programs. This includes a wide range of tasks such as

- Surveillance
- Facility characterization
- Surface decontamination
- Hot cell dismantlement
- Handling and removal of parts

in order to minimize human exposure and improve overall efficiency. Because of the large size of the facilities, instruments and components, most of the tasks require dual-arm manipulator systems deployed by either structurally-fixed or vehicle-based crane systems.

2. Breakdown of Major D&D Tasks

Main D&D tasks are categorized in eight areas. These include activities from regular inspection-related ones to dismantlement and removal of systems that are no longer used or needed. We briefly review these tasks below in order to give an idea on the magnitude of the problem. The breakup of tasks are given as follows:

- Surveillance
- Facility characterization
- Surface decontamination
- Hot cell dismantlement
- Handling of large and heavy objects
- Packaging
- Transportation
- Storage

2.1 Surveillance

Surveillance entails regular inspection of nuclear sites and storage areas to assess existing conditions, and to detect any leakage that may occur. In addition to visual inspection, contamination levels are monitored by sensors such as radiation sensing devices. In order to make a better assessment of conditions, swipe samples are also gathered from critical locations for later analysis.

2.2 Facility characterization

To conduct surveillance, decontamination, and dismantlement tasks remotely by robotic systems, one of the first requirements is to have a fairly detailed description of the site to be worked in. Since reactor environments are highly unstructured and dynamic, obtaining the most current description, or map, of the area to be worked in becomes an essential first step before any other task is accomplished. If an earlier plant model exists, it should be reconciled with the existing plant conditions by introducing the differences in the present environment and the older model.

Because there is no standardization in plant designs or their descriptions, most available information will be in the form of engineering drawings of the original structures with perhaps some appended update information. Transformation of existing descriptions to a standard 3-D CAD environment will provide the first level of facility mapping efforts. Characterization of a partial view (onion scale) of the scene should be emphasized instead of a bird's eye view since tasks can only be conducted in the immediate vicinity of the robotic system. Hence, the created graphical image will not be cluttered with unnecessary information and also the computational demand will be kept at a reasonable level making real-time processing possible.

In order to update the existing database to the most current level, one will have to find a means to determine the differences and include them to the plant description. This is achieved by sending into the facility a mobile camera system and, if possible, reconciling the differences automatically. Since complete automation will either not be possible or not reliable enough, human intervention to teach or approve changes is needed. This concept is illustrated in a feedback control scheme in Figure 1.

After sufficient experience is built in model updating, it will be carried out concurrently with other types of data acquisition; e.g., contaminant, temperature, and humidity data. This reduces the overall D&D task times since the mobile system will cover a section of the facility only once to gather all the necessary information prior to conducting other D&D tasks.

Figure 1. Plant characterization via reconciliation in models

2.3 Surface decontamination

Once the current facility maps are generated, remote inspection and decontamination tasks can be carried out much more reliably. For this purpose, most commonly, robots equipped with radiation sensors are used for contaminant characterization. In some cases, swipe samples are needed to analyze the contents outside in a laboratory where more elaborate tests are conducted.

Other tasks for decontamination involve spraying, washing and scrubbing. A repetition of contaminant characterization is needed after the decon operations to record contamination levels before further steps are taken.

2.4 Hot cell dismantlement

After the contamination is verified to be at an acceptable level, dismantlement operations take place. This involves the typical machine shop operations such as cutting, sheering, drilling, and so on. In addition to providing the hand-held versions of these tools nearby the robot, it is imperative to use a dual arm system where the second arm guides, or assists the first one just as humans use their arms when they dismantle systems.

2.5 Handling of large and heavy objects

An ability to handle relatively large objects is a necessary attribute in D&D applications especially when robots are used for this purpose. Although the payload/weight quotient has been improving considerably in the past few years, the

majority of existing industrial robots weigh too much and carry too little. Payload/weight quotients for some industrial robots are given in Table 1. This table indicates that hydraulically-powered robot systems are more suitable to electrically-driven manipulators for D&D tasks.

Table 1. Comparison of payload capacity and weight of some industrial robots

Robot	Payload P (lb)	Weight W (lb)	P/W
Cincinnati Milacron T3-726*	14	2,000+	0.007
Robotics Research K/B-1207*	20	160	0.125
Spar 2500 Series**	2,500	15,000	0.167
TeleRobotics International TeleMate*	26.3	92.4	0.285
Schilling Titan III**	240	185	1.297
Schilling Titan II**	240	175	1.371
* Driven by electric motors. ** Actuated hydraulically.			

2.6 Packaging

Packaging deals with assembling dismantled parts or pieces together into a suitable bundle for transportation to another site. If contaminated, parts will have to be placed into special canisters and sealed, which makes this task more demanding.

2.7 Transportation

Packed units are loaded on to vehicles for either further processing or storage purposes. Due to large weights of canisters and drums, their loading is done by vehicle-based cranes.

2.8 Storage

This task requires unloading of the canisters after transportation where the operations involved in the packaging are reversed if further processing is required. Otherwise, the packages will be ready for storage.

3. Existing Robotics Technology

3.1 Overview of industrial robots

State of the art in industrial robotics has advanced considerably within the last few years [1]. Most remarkable in this area, perhaps, has been the development of modular robot designs which reduced robot weight considerably while increasing payload capacities. This, of course, was possible by incorporating new technologies as soon as they became available. A recent survey carried out for a DOE study revealed that for medium-scale, regular nuclear reactor tasks, such as the maintenance tasks of Advanced Liquid Metal Reactor (ALMR), the following robots were found to be most suitable [2]:

Table 2. Three industrial robots suitable for medium-scale reactor maintenance tasks

• <i>Robotics Research Arm K/B-1207 (and K1207i)</i>   • <i>Odetics Dexterous Manipulator</i>   • <i>TeleRobotics International, Inc: TeleMate</i>

These three manipulators represent more recent robot designs which are recognized by their lighter weights and higher payloads. All three employ electrically-driven motors and are suitable for medium-scale maintenance and manufacturing tasks. Originally marketed for space applications, the Robotics Research Manipulator actually represents the first commercial robot where mechanical modularity was introduced. However, interchangeability of modules is not done by the user. Rather, the company fabricates a number of scalable joint modules and produces different models by using different modules [3]. The general concept of modularity where three robots are built by using a limited number of joints is illustrated in Figure 2. Two cooperating Robotics Research robots are shown in Figure 3.

The Odetics Dexterous Manipulator also enjoys a modular design as well as some elements of fault tolerance [4]. This seven-degree-of-freedom manipulator employs fourteen electric motors; thus, each joint has one degree of fault tolerance against actuator failures. It also uses redundant sensors (encoder and potentiometer combinations) to improve system reliability against sensor failures. In fact, fault tolerance of a robotic system can be strengthened at four levels [5]. These levels are given as follows:

- Joint level by using dual actuators
- Module level by incorporating parallel structures
- Robot level by employing redundant manipulators
- System level by making use of multiple robots

By comparison to the Robotics Research and Odetics robots, the TeleMate has more modest design features, but it targets reactor maintenance applications directly, and it is

produced by a company with solid experience in nuclear reactors. Although no precise information was available, all three companies were taking steps for shielding sensitive components (mostly against low energy gamma rays). For this purpose, the Robotics Research has produced its "i" series of robots (models K-807i and K-1207i). Various characteristics of these three robots are tabulated in Table 3 for easy comparison of their properties.

This class of medium-scale electric robots are suitable only for light D&D tasks where peak payload demand will not exceed 50 lbs, and where accuracy demands get quite high (0.001–0.002 in).

Figure 2. Modularity allows construction of robots with different capabilities

The relatively high payload demands of decontamination and dismantlement tasks suggest that hydraulically-driven robots are more suitable relative to the robots which use electric motors. Among the companies that produce hydraulic robots, Schilling Development designed a very successful line of robots called the Titan series. Also, Spar introduced its 2500 series remote manipulators specifically designed for heavy-duty tasks and hazardous environments. Because of their potential to be used in D&D operations, we will separately review these robot below.

In general, robots that use fluids or foreign material are not encouraged for use in nuclear environments in order to limit the contaminant level. This requirement does not seem to be too severe for ordinary maintenance tasks, and it usually translates to the

employment of electric robots. They are preferred over hydraulics since they are clean, quiet, reasonably reliable, and available in a wide variety of brands, models, and prices. Because they are also preferred in industry for assembly and other applications, electric robots have become de facto standard in robotics. However, for special needs, other sources of actuation should be evaluated for possible use.

Table 3. Comparison of three electrically-driven industrial robots

Model	Robotics Research Arm K/B-1207	Odetics Dexterous Manipulator	TeleRobotics International Inc: TeleMate
Weight (lb)	160	165	92.4
DOF	7	7	6
Payload (lb) Continuous: Peak:	20 NA	20 50	26.3 33
Max. Reach (in)	47.2	55	39.3
Accuracy (in)	0.002	0.001	0.002
Drive	DC Motors w/ Harmonic Drives	Brushless DC Motors	Brushless DC Motors
Backlash	Yes	No	Yes
Footprint (in x in)	Max 10 x 10 (Est.)	Max 10 x 10 (Est.)	10 x 10
Max. Speed (in/sec)	40	40	Greater than 33
Construction Material	Cast Aluminum, Steel	Stainless Steel, Aluminum Alloys (Est.)	Stainless Steel, Aluminum Alloys
Modularity	Yes (Limited)	Yes	No
Allowable Amb. Temp Range (°F)	32 – 100	Less than 100 (Est.)	Less than 100 (Est.)
Active Cooling System	No	No	No
Shielding	No	No	Yes
Compactness	High	High	Medium
Ease of Decon	V. Good	V. Good	Good
Cost (US \$)	150–200K	NA	200K
NA: Not Available, Est: Estimated.			

D&D tasks present such a unique case where the magnitude of payload drives the entire design. Moreover, in these applications, accuracy does not present itself as a critical issue. Since the companies building hydraulic robots have also targeted the nuclear industry, leakage and dependability problems are being addressed more rigorously than before. As a result, hydraulic robots present themselves as the only feasible solution for most of the D&D needs.

Figure 3. Two Robotics Research Arms
in dual configuration

3.2 Schilling and Spar manipulators

Schilling Development, Inc. is one of the few, but very successful, companies which produces hydraulic manipulators. Their rugged robots are used in the construction of offshore structures, and for regular inspection, maintenance and repair of oil rigs, and undersea wellhead servicing operations.

For instance, the Titan II robot depicted in Figure 4, one of the Schilling robots, is the second-generation design of the original Titan arm where many component designs have been refined. Although it can operate in deep-ocean applications, a special version of the arm tolerates an accumulated exposure of 10^7 RAD (gamma radiation) without any loss in performance. It enjoys a relatively high payload (lift) capacity of 240 lbs, while the use of titanium in its construction allows the total weight to be only 175 lbs. For a 76.3-inch arm, this gives one of the best payload/weight quotients as we have seen in Table 1. In order to improve the Titan's workspace, RedZone Robotics is building a three-degree-of-freedom presenter (two orthogonal revolute joints each with $\pm 90^\circ$ rotation, and one prismatic joint with 18 inch translation) to mount two Titan II robots at the Oak Ridge National Laboratory [6]. Two Titan II arms in dual configuration is illustrated in Figure 5.

Properties of three Titan arms are compared in Table 4. Although these three arms are essentially the same, Titan III introduces many small but important refinements in its design over its predecessors. These include revisions in design to reduce actuator backlash and friction, installation of pre-loaded, tapered roller bearings to eliminate backlash, clean exterior surfaces with reduced forearm pockets to ease decontamination, and analog-to-digital processing on board the robot [7, 8].

Spar's 2500 series remote manipulator systems are specially designed for hazardous environments and are capable to carry payloads up to 2,500 lbs. This robot has a maximum vertical and horizontal reach of 28 ft (8.5 m), and is six degrees of freedom; an optional linear track adds the seventh degree of freedom. All operations of the arm is controlled from a remote operations center. One of the Spar arms in Figure 6 is used to remove, inspect, and replace large components in the radioactive core of CANDU reactors in Canada. Some of the specifications of this robot are given as follows:

- Maximum Payload: 2,500 lb (1,134 kg)
- Repeatability: 0.05 inch (1.27 mm)
- Resolution: 0.05 inch (1.27 mm)
- Linear tip speed: 0–24 in/sec (0–610 mm/sec)
- Reach: 28 ft (8.5 m)
- Weight:
 - Arm assembly: 15,000 lbs (6,804 kg)
 - Carriage: 8,700 lbs (3,946 kg)
 - Base track: 8,500 lbs (3,856 kg)
- Linear track movement range: 207 inch (5.2 m)

Figure 4. Titan II hydraulic robot by Schilling Development

Figure 5. Two Titan II robots in dual arm configuration (Photo by RedZone Robotics)

Figure 6. Spar 2500 series remote manipulator

3.3 Schilling and Kraft manual controllers

Schilling Development, Inc. designs hydraulic telerobots which are directly controlled by an operator through a manual controller. The operator guides the slave robot via a master arm (manual controller) for position or velocity control of the end-effector motion. In addition to this, a version of the manual controller incorporates force feedback feature which usually feeds back the forces experienced by the robot's end-effector to the operator to correct his/her input motion. Oak Ridge National Laboratory's servomanipulator development represents one of the early designs based on such a concept [9].

In general, telerobotics is more suitable for maintenance and repair tasks in unstructured environments as opposed to repetitive assembly-type tasks where the environment is more structured, and constant human supervision is not necessary. Extensive studies have been conducted at the Oak Ridge National Laboratory by Draper, and Hamel et al. on human factors in the remote control and telerobotics areas where operators evaluated many different setups with and without force reflection [10–15]. Force feedback provides extra information to the operator who tries to accomplish a task at a remote site. Hence, this extra information improves operator confidence, and generally reduces operation times. Because of these attributes, use of force reflection is desirable in D&D tasks.

Schilling offers two optional manual controllers; one for position control only, and the other for both position and force control purposes. The unit, called Compact Master Console, is indeed compact as shown in Figure 7, and kinematically it is a

scaled-down version of the Titan series arms. Some of the specifications of the Master Console for the Titan 7F and Gamma 7F are given as follows:

- Height: 10 inches
- Width: 6 inches
- Length: 19 inches
- Weight: 10 lbs

Table 4. Three hydraulic Titan series manipulators by Schilling Development

Model	Titan II	Gamma 7F	Titan III
Weight (lb)	175	147	185
DOF	6	6	6
Payload (lb) Continuous	240	250	240
Max. Reach (in)	76.3	78	76.3
Accuracy (in)	NA	NA	0.1
Drive	Hydraulic oil 3000 psi nominal	Hydraulic oil 3000 psi nominal	Hydraulic oil 1.5 to 5 gpm @ 3000 psi nominal
Backlash	Yes	Yes	Reduced
Construction Material	Titanium	6-4 Titanium	Titanium
Modularity	No	No	No
Allowable Amb. Temp Range (°F)	32 to 120 est.	32 to 120 est.	32 to 120
Active Cooling System	No	No	No
Shielding	10 ⁷ RAD gamma	10 ⁷ RAD gamma	10 ⁷ RAD gamma
Compactness	Medium-high	Medium-high	High
Ease of Decon	Good	Good	V. Good
NA: Not Available, Est: Estimated.			

Schilling markets this controller primarily for Remotely Operated Vehicles (ROVs) and manned submersible systems. It is suitable for use in most routine inspection, maintenance and repair purposes where the telepresence concept is acceptable.

Kraft TeleRobotics offers a force reflecting hand controller which represents the best such design so far in the market. The controller has six degrees of freedom and is

very compact. A space-qualified version of this manual controller is produced by the joint efforts of Martin Marietta and Kraft TeleRobotics. Some of the properties of this controller are listed as follows:

- Size (folded position): 9×10×15.5 inches
- Maximum reach: 20 inches
- Maximum reflected force: 5 lbs
- Weight: 25.6 lbs.

Figure 7. Schilling Master Console controllers

It supports position, rate and force control modes, and the scaling of position and force reflection factors. This feature allows the user to adjust the resolution of motion to improve accuracy, and the magnitude of force feedback to avoid fatigue. The original Kraft hand controller and the Martin Marietta/Kraft TeleRobotics manual controller are shown in Figures 8 and 9, respectively.

4. Robotics Component Technologies

4.1 Structural design

Structural design of robots was not very successful until very recently. Most robots had a bulky design and relatively modest performance. By contrast, recent designs especially the ones reviewed in this paper, represent a significant improvement in the area of structural robot design. Modular robot design introduced by Robotics Research was a new approach never tried before in robotics (at the mechanical component level). Remarkably improved aesthetics of this arm, coupled with its very dexterous workspace set the stage at a higher level for the future of robot design.

As Robotics Research implemented the modularity concept, Odetics integrated some fault tolerance features to its seven-degree-of-freedom robot. Although somewhat expensive, this robot represents the state of the art in robot design with both its

modularity and fault tolerance capabilities, and very clean mechanical design. Titan arms by Schilling and Kraft force reflecting manual controller by Kraft Telerobotics also represent some of the recent successful designs.

Although these positive developments are encouraging, we must note that the payload capacity of hydraulic and especially the electric robots remains relatively low. Improvement of the end-effector lift capacities will make robots more useful in new areas which are not even considered today. This will be achieved by new actuator technologies where torque output/weight ratio is increased, and also by developing new materials with higher strength/weight ratios.

Figure 8. Kraft TeleRobotics force reflecting manual controller

4.2 Actuators

As mentioned above, the aim is to design new actuators which increase the motor torque output relative to the actuator weight. In this regard, electric motors have an inherent disadvantage over hydraulic actuators. As new, more efficient drive units (gear sets) are designed, and new materials are incorporated, electric motors will perhaps be continuously improved. Meanwhile, for tasks which demand high payloads, hydraulic robots such as the Spar and Titan arms offer the most suitable solution.

4.3 Drive units

Earlier robots employed spur gears to reduce speed and boost torque output; however, they also introduced an unacceptable level of backlash. Later, harmonic drives became very popular. Although these drives do reduce backlash considerably, they do so at the expense of considerably increased friction. Recent developments indicate that a new drive system, called Sumitomo drive units, has the potential to provide a compromise solution between either high backlash or high friction.

Figure 9. Space-qualified hand controller
by Martin Marietta/Kraft Telerobotics

4.4 Sensors

Higher expectations on sensory performance will perhaps not diminish as long as the robots are expected to behave more like the humans. This means that robots should not only be equipped with more sophisticated sensors, but the quantity of sensors should also increase as more varieties of sensors are installed for improved sensing. As this is realized, timely processing of all the gathered data and their interpretation at acceptable speeds; or sensor fusion, will gain even more importance.

4.5 Materials

Materials used in a robot forms one of the most crucial decisions in the design process since it determines arm's strength as well as its overall weight. Of course, robot's weight directly influences the payload capacity. Recent designs have used materials such as engineering materials, titanium, aluminum alloys and stainless steel. Composite materials were also tried, but it is generally not recommended for use in contaminated areas. (Here, the implication is that composite materials become brittle when exposed to radiation over extended periods of time. This claim might be inconclusive at the present time, and further findings should clarify it.)

4.6 Shielding

Most industrial robots do not provide shielding since they are intended for industrial use. Among the robots reviewed in this study, only the Telemate and Titan arms claim some shielding against gamma radiation. Recently, the Robotics Research started to produce the "i" series robots (K-807i and K-1207i) which are expected to withstand low level gamma radiation, but the company declined to give specific information on radiation levels. Titan robots withstand gamma radiation up to 10^7 RAD. Spar 2500 manipulators are also radiation resistant.

The previous study in [16] suggests that low level gamma rays can be avoided by simply protecting the sensitive electronic equipment. A survey during this study revealed that most electronic components are available in a radiation-resistant version, which further eases the implementation of shielding. If, however, free neutrons exist while robot operates in a facility, then hardening of components will be necessary. Since hardening techniques evolve around using layers of lead, it negatively affects the payload capacity of robots. Hardening of various computer chips is being studied experimentally at the University of Florida by Tulenko et al. [17]. Effects of radioactivity on position sensors is studied in [18, 19].

4.7 Cooling

The electric robots in Table 3 operate between 32 and 100°F, whereas the Titan arms in Table 4 tolerate up to 120°F. It is interesting to note that most electronic equipment are rated at around 120°F for their maximum operating temperature [16]. Although the 120°F maximum temperature is acceptable for most D&D tasks, in cases where higher temperatures are expected, one can cool sensitive equipment by using the vortex tube technology [2, 16].

Figure 10. Vortex tube (Vortec Co. Model 208)

Vortex tubes, shown in Figure 10, are simple devices. They convert the compressed air into two flows: one of hot air and one of cold air. A vortex tube operating with 100 cfm of compressed inlet air at 100 psig and 70°F can produce cold air at -50°F. Vortex tubes built by Vortec Co. have cooling capacities from 100 to 6,000 BTUH. Various advantages of a vortex tube are listed as follows:

- Simple design with no moving parts
- Operates only on compressed air
- Electricity is not needed
- Air flow rate and output temperature can easily be adjusted
- Effective to cool enclosed volumes (i.e., actuators, sensors, etc.)
- Maintenance-free operation.

As illustrated in Figures 11 and 12, a vortex tube is used to cool a sensor module (outside dimensions measured approximately 5×5×5 in.) which contained three CCD cameras to visually inspect the reactor and containment vessels of ALMR (Advanced Liquid Metal Reactor) under development for DOE by a consortium of companies and universities led by General Electric San Jose, California. This cooling system is successfully tested in a laboratory testbed [2, 20].

Figure 11. Vortex tube attached to a sensor module to cool three CCD cameras

Figure 12. Vortex tube attached to the prototype sensor module

4.8 Controllers

In addition to the traditional forms of visual and force feedback, provision of a virtual reality environment will enhance replication of the remote scene for the operator. As new technologies develop and become feasible, use of 3-D monitors, stereo sound for input and feedback purposes should also be considered in teleoperation.

At lower levels of the control hierarchy, advanced intelligent controllers will allow the most efficient use of the robotic system. This includes continuous monitoring of components, resource allocation and system reconfiguration should failures occur. After a failure or an unexpected event, the system isolates the failure and uses the remaining resources to complete its task as gracefully as possible without any interruption in the originally planned operation [21].

5. Recommended Robotic System

In order to assess the maturity of robotics technology, we first list the major demands of D&D tasks, then review the target areas of present robotics technology, and then assess whether there exists sufficient overlap between the demands of D&D and the offerings of robotics. D&D tasks show the following major attributes:

- *Hazardous environments*
Some facilities have a high level of contamination.
- *Unstructured environments*
Exact location, shape, and condition of items are not always available.
- *Oversize, heavy objects*
Dismantlement deals with taking apart facilities that are inherently very large. (In order to give an idea of the magnitudes involved, one should consider that a reactor vessel alone measures on average 30 ft in diameter and 80 ft in height. These facilities have many floors under ground as well as above it.)
- *Complicated tasks*
Dismantlement tasks are complicated which demand high-level skills.

By contrast, most of today's robots are built for

- *Non-hazardous environments*
- *Structured environments*
- *Small, light objects*
- *Simple tasks*

Here, our aim is to stress that the target of mainstream robotics technology is not directly coincident with that of D&D needs. This is evident, for example, in the existing designs of electric and pneumatic robots which can not carry heavy objects or work in hazardous environments. Their controllers are designed for rudimentary pick-and-place type functions and are meant to operate in autonomous mode which implies highly structured surroundings.

By satisfying the required magnitude of D&D tasks, crane and vehicle-based hydraulic robots offer solutions to D&D tasks. For more modest tasks, where smaller payloads, but more precise operations are desired, electric motor-based robots should also be considered. Because of the complexity of the dismantlement operations, use of multiple arms will be necessary. While a crane transports the robotic system of multiple manipulators to the work site, one of the arms will clamp to a support nearby the work area; thus, reducing oscillations of the entire system. Other arms will tool themselves and carry out D&D tasks.

Remote control of the robotic system needs to be monitored from a control center with adequate visual, graphical, and force feedback. Various options to input operator commands through a joystick, voice, or a touch-screen monitor should be provided. Simplicity of the interface is important in order not to confuse the user.

The basic technology required from the robotic system described above is currently available. For hydraulic-based robots, Schilling six-degree-of-freedom Titan,

and Spar 2500 series remote manipulators qualify for D&D tasks. The Titan arms withstand low energy gamma rays up to 10^7 RAD, lift payloads up to 240 lbs, and provide interface for remote control. The Spar robot, with a payload capacity of 2,500 lbs, targets very heavy-duty tasks; however, it appears that its original design does not intend the arm to be used as a transportable system (arm weight alone is 15,000 lbs) without any modifications.

However, if a Spar 2500 robot is mounted on a vehicle, it will offer a much desired capability to carry other robotic systems near the worksite. With a total weight of 350 lbs, dual Titan arms in Figure 5 are ideal candidates to be carried by a Spar arm which boasts a payload of 2,500 lbs.

For small-scale tasks, the Robotics Research K-1207i or Odetics Dexterous Manipulators are suitable choices. Both of these robots offer seven degrees of freedom, and are resistant against low energy gamma rays. They enjoy noticeably larger and more dexterous workspaces due to their extra (redundant) degree-of-freedom. This redundancy allows these robots to avoid obstacles more easily than their non-redundant counterparts. TeleRobotics International's TeleMate is also a reasonable alternative for more modest tasks. These robots may also be mounted at the end-effector of a Spar manipulator to reach high or difficult-to-reach locations.

Kraft Telerobotics produces a six-degree-of-freedom force reflecting manual controller which can feed back forces of up to 5 lbs directed towards any direction in its workspace. Although the Kraft manual controller is the best available commercial system, Schilling's Compact Master Console is another alternative to control manipulator systems described above. Since all manipulators will not be purchased from one company, or different manipulators will be added later on, it is important to design the remote control interface and the manual controller universal, which means that it should be able to control any robot regardless of its geometry or manufacturer.

6. Future Developments in Robotics Technology for D&D Operations

The robotic system described above represents the state of the art in existing robotics technology suitable for D&D tasks. Of course, as incremental improvements in component technologies are integrated into the existing state of the art, benefits of the implementation will steadily increase. For example, tasks which require larger payloads will not be viewed as problematic. Higher precisions will be attained more easily, and tasks will be completed faster as machine/human interfaces are enhanced.

D&D operations will directly benefit as the following robotics component technologies are further developed and integrated into the existing designs:

- *Actuators*
 - Higher output torque
 - Reduced weight
 - Lower friction
 - Decreased backlash
 - Minimum deflection
 - Resistance to radiation
 - Resistance to high temperatures

- *Materials*
 - Higher strength
 - Lower weight
 - Radiation resistance
 - Tolerance to high temperatures
- *Structural Design*
 - Standardization
 - Modularity
 - Allowance for fault-tolerance
 - Incorporation of radiation-tolerant components
 - Provisions for add-on cooling systems such as vortex tubes
 - Open architecture philosophy for easy interface
- *Sensors*
 - Miniaturization
 - Fast information processing
 - Data fusion
 - Self diagnostics and failure isolation
 - Radiation-resistant sensors
 - High-temperature-resistant sensors
 - Voice synthesis and analysis
 - Realistic virtual reality implementation
 - 3-D monitors
- *Controller*
 - Robust controllers
 - Fault-tolerant controllers
 - Introduction of monitors with 3-D image capabilities
 - Incorporation of virtual reality into teleoperation systems
 - Use of voice for feed back to the user (voice synthesis)
 - Instructions to the robot via sound (voice analysis)
 - Easy-to-use GUI
 - Modular software
 - Open architecture for interface to other systems
 - Radiation-tolerant versions of controller hardware
 - High temperature-tolerant versions of controllers

7. Conclusions

D&D tasks challenge the current robotics technology, because they demand vehicle-based robots (roughly in the earth-mover scale or larger), which can operate in contaminated areas to accomplish complicated tasks with, at times, relatively tight precision requirements. In this paper, major D&D tasks and their requirements are reviewed against the existing robotics technology. It is recommended that a number of commercial hydraulic and electric robots and manual controllers to be used for current D&D needs. These include Schilling's Titan Series Robots, Titan II, Gamma 7F, and Titan III, Spar 2500 Series Manipulator, Robotics Research K-1207i Robot, Odetics Dexterous Manipulator, TeleRobotics International's TeleMate Manipulator, and Kraft TeleRobotics Hand Controller. In order to carry out the demanding dismantlement tasks, two, three, or more of these robots need to cooperate with each other just as humans use both of their arms, or a number of them work together when they deal with a larger task.

For the successful operation of the robotic system, development of an innovative remote control interface system is essential. Such a system should integrate components such as 3-D vision, stereo vision and sound, voice input-output, and virtual reality to enhance interface with the operator. Development of intelligent, fault-tolerant controllers, and establishment of hardware and software standards will not only enhance D&D tasks, but will also advance the robotics technology itself.

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