SAND2000-0562C

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ROBOTIC SYSTEM FOR GLOVEBOX SIZE REDUCTION*

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ABSTRACT

The Intelligent Systems and Robotics Center (ISRC) at Sandia National Laboratories (SNL) is developing technologies for glovebox size reduction in the DOE nuclear complex. A study was performed for Kaiser-Hill (KH) at the Rocky Flats Environmental Technology Site (RFETS) on the available technologies for size reducing the glovebox lines that require size reduction in place. Currently, the baseline approach to these glovebox lines is manual operations using conventional mechanical cutting methods. The study has been completed and resulted in a concept of the robotic system for in-situ size reduction.

The concept makes use of commercially available robots that are used in the automotive industry. The commercially available industrial robots provide high reliability and availability that are required for environmental remediation in the DOE complex. Additionally, the costs of commercial robots are about one-fourth that of the custom made robots for environmental remediation. The reason for the lower costs and the higher reliability is that there are thousands of commercial robots made annually, whereas there are only a few custom robots made for environmental remediation every year.

One of the unique enabling technologies of this conceptual study is the use of graphical programming and robot motion planning and control software, which are the keys to using commercial robots in difficult environments such as environmental remediation. Commercial robots are typically used in repetitious operations where reprogramming of the robots is infrequent. The ISRC-developed software for automatically programming robots is being evaluated for use in environmental remediation applications, which requires the robot to perform a different task frequently. The paper will describe the engineering analysis approach used in the design of the robotic system for glovebox size reduction.

INTRODUCTION

The Intelligent Systems and Robotics Center (ISRC) at Sandia National Laboratories (SNL) is developing technologies [1] for glovebox size reduction in the DOE nuclear complex [2]. Size reduction and packaging of diverse equipment is essential to Deactivation and Decommissioning of the Building 771 and 776 facilities at Rocky Flats to meet closure goals by 2006.

The current baseline approach to size reduction in DOE facilities is to use conventional commercially available tools with manual operations. Automated cutting will need to address management of the work pieces. Animation showing the cutting process and discussion on the issues has been developed to help explore these issues.

* This work was performed at Sandia National Laboratories, a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

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This paper describes a study that was conducted in the Intelligent Systems and Robotics Center of Sandia National Laboratories to develop technologies for glovebox size reduction in the DOE nuclear complex. The study was performed for Kaiser-Hill at the Rocky Flats Environmental Technology Site on the available technologies for size reducing the glovebox lines that require size reduction in place.

STATEMENT OF THE PROBLEM

The target problem for the design study was a robotic system that is capable of size reducing the Fluorinater Lines (Lines 6 and 7 in Building 771). The cutting technology chosen determines the types of cuts that need to be made. While the laser that is available for fiber optics delivery could only cut up to 1/4 inch of sheet stainless steel (in the continuous power mode), plasma torches cut thicker material. It must be noted that to perform these cuts, the cutting device needs to both have sufficient power and agility to cut through the rapidly varying thickness.

Thin and Thick Cuts

Figure 1 shows the different types of cuts. As shown in Picture A of Figure 1, red lines have been drawn on the image to indicate likely cuts that would need be made with a laser system. The blue lines indicate alternative options using a higher power, more agile technology, or conventional technologies that are capable of cutting thicker stainless steel.

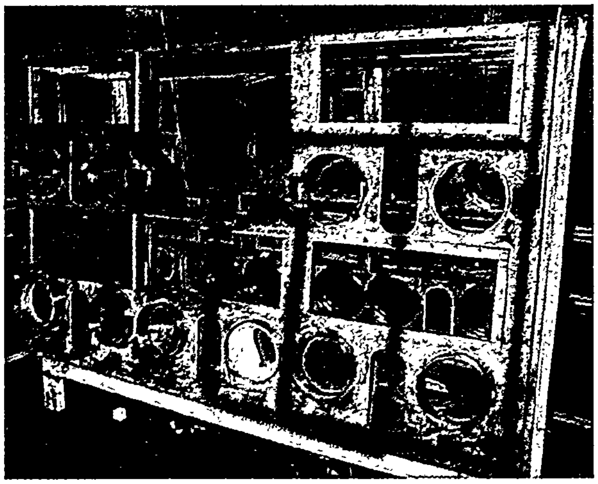
Cutting Interference

Picture B of Figure 1 shows typical hardware that might interfere with cutting operations. Stainless steel Unistrut was often welded into the inside top and sides of gloveboxes to provide inside handling and fixturing points. The Unistrut may be particularly difficult to cut with any torch device. However, because the cut could be done from the topside, alternative methods are available to address this need. For example, conventional cutting methods such as a hydraulic shear may be appropriate for this application.

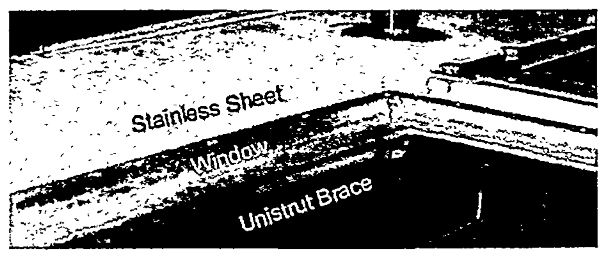
Cuts with Waterwall

A waterwall is a weldment, usually welded on the outside of the glovebox, designed to contain water which is used to shield neutron radiation. Gloveboxes with waterwalls present an additional set of complexities to the cutting problem (see Picture C, Figure 1). For example, the Line 6 and 7 gloveboxes have three wall layers. Here, the inner wall and first waterwall were part of the initial construction while the outer waterwalls were added at a later date. Gloveports and windows are rigidly welded to both the inner and first waterwall while the outer waterwall is welded to the first waterwall surface.

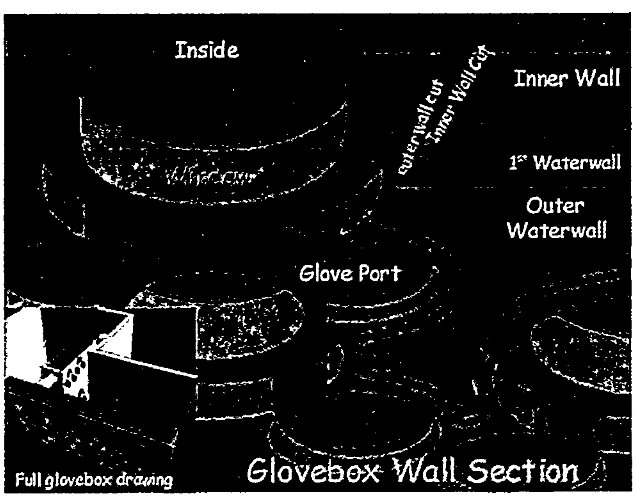
Size reducing the glovebox in Picture C of Figure 1 will require cutting away maximal amounts of each waterwall to expose the surfaces they cover. For example, the cuts show an approximate cut path that might be performed on the outer waterwall to expose the first waterwall. It should be noted that these cuts need to remove the material between the glove ports. Cuts on the first waterwall will then need to again remove the material between the various features while at the same time be shifted inward to avoid having the cutting torch hit the edge of the outer waterwall. Special considerations are required when cutting through the edges or corners of the outer layer to further expose the inner wall. Finally, the inner wall can be removed by cutting around, rather than between the glove ports and other features.



A. Thin and Thick Cuts



B. Cutting Interference



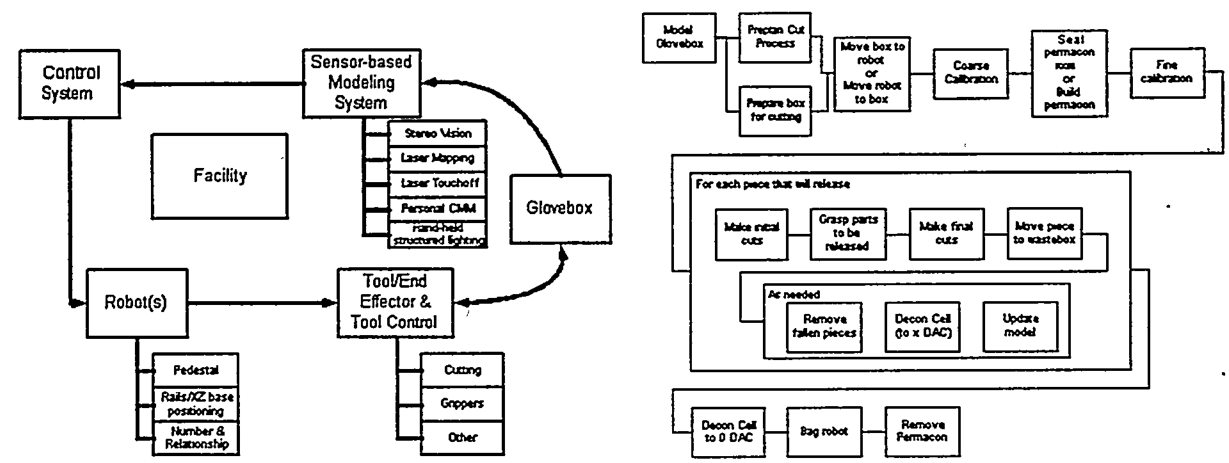
C. Cuts with Waterwalls

Figure 1. Types of Cuts

SYSTEMS APPROACH TO DESIGN

RFETS requested Sandia to perform a design study for implementing the needed technologies for in-situ size reduction of the Fluoride glovebox lines in Building 771. This system would be based on industrial pedestal robots as opposed to custom-made gantry type robots. In addition, while the system was initially targeted to support a size reduction facility (based on the hard-side facility), it should be designed for eventual adaptation for in-situ glovebox size reduction. Finally, to allow this broad depth of capability while still meeting RFETS milestone targets, the system should be designed for implementation in phases. The initial phase would be focused on cutting within a size reduction facility, and then gradually would expand the capability to support automated scrap handling and improve its operational efficiency through better sensing and autonomous remote control.

The functions of the proposed system are shown in Diagram A of Figure 2. The control system combines graphical programming [3] with established telerobotic [4] features. A variety of industrial robot models, tools for cutting, grippers, software tools, and other uses were investigated [5]. In addition, the number and task distribution for multiple robots, robot base, or XZ positioning (lift and translation) approaches were evaluated. A variety of sensing technologies was also evaluated for model building and calibration. These included laser-range finders (laser touchoff), stereo vision, personal coordinate measuring, and robot or handheld structured lighting.



A. Functional Diagram of the Robotic System **B. Systems Approach to Design**

Figure 2. System Approach to Design

While the robotic hardware issues are straightforward, sensing and control features must be optimized with respect to the broader workflow issues for transforming in-place gloveboxes to Waste Isolation Pilot Plant (WIPP) ready waste. For example, the use of models in graphical programming allows operators to directly insert process schedules into the robot's operating system. This capability was used in the glovebox cutting experiment and resulted in a significant decrease in operation time over performing the process development in an ad-hoc manner (both methods were tested).

To better understand the system implications of workflow, the following operational process was developed:

- Create initial model of glovebox (in-situ)
- Plan cut-down process. Determine:
  - Order of cuts
  - Part/robot placement (glovebox relative to robot)
  - 1st order contingency plans (i.e., identify potential upsets)
- Prepare glovebox (remove windows, covers, pipes)
- Move glovebox to robot or robot to glovebox (move glovebox or robot and repeat next 3 steps as needed)
- Calibrate/model glovebox in cell
  - Coarse calibration
  - Fine calibration
  - Possibly dry-run cuts
- Initiate cutting and part removal (or let parts fall)
- Update model, execute contingency plans, create new plans as needed
- Locate, model, and retrieve fallen scrap and debris
- Decontaminate cell for next part or bagout robot for next in-situ operation

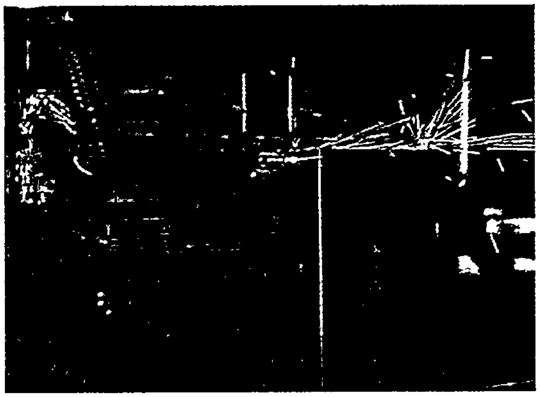
Diagram A of Figure 2 represents the above operational process.

One way to analyze the system-level design is to form each function, as shown in Diagram B of Figure 2, into a matrix of functional requirements and design parameters. Such a mapping provides the designer with a clear path for linking sub-component design requirements to the system feature that it directly impacts. In addition, analyzing the degree to which various requirements are met by separate design elements helps the system designers to better understand the coupling between design parameters. (Less coupled designs are easier to implement and support.) Such a systems analysis has been done for the concept above. The analysis shows that coupling between elements will be minimal and the system design appears to be robust.

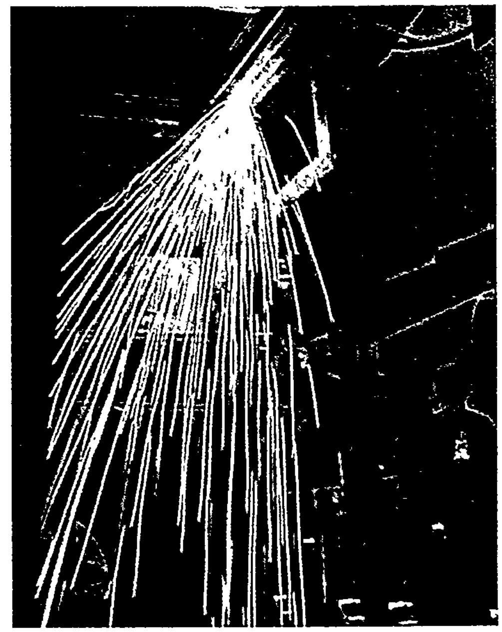
EXPERIMENTAL VERIFICATION

Sandia performed two sets of experiments to test the extent robots can be used for size reduction as required by this design. Figure 3 shows a pictorial sequence of the system approach to design.

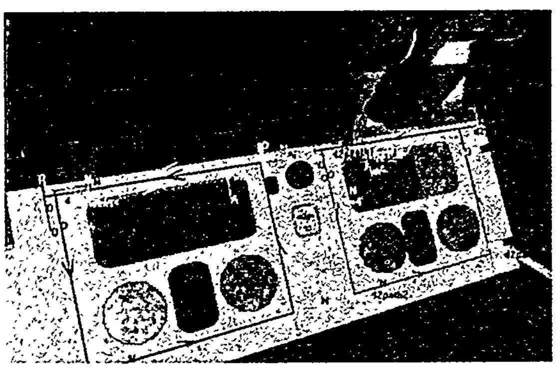
The first set of experiments tested the raw capability of a ND-YAG (Neodymium-Yttrium Aluminum Garnet) laser deployed on a robotic arm. Picture A of Figure 3 shows the setup of the first set of experiments. These experiments showed that the laser was fully capable of cutting 1/4" stainless steel parts at rates of 33 inches per minute. This experiment was witnessed by a variety of DOE and site contract employees.

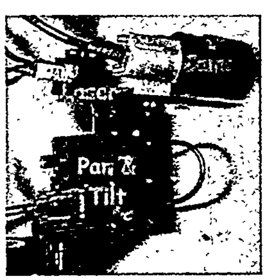


A. Experimental Determination of Laser Capabilities

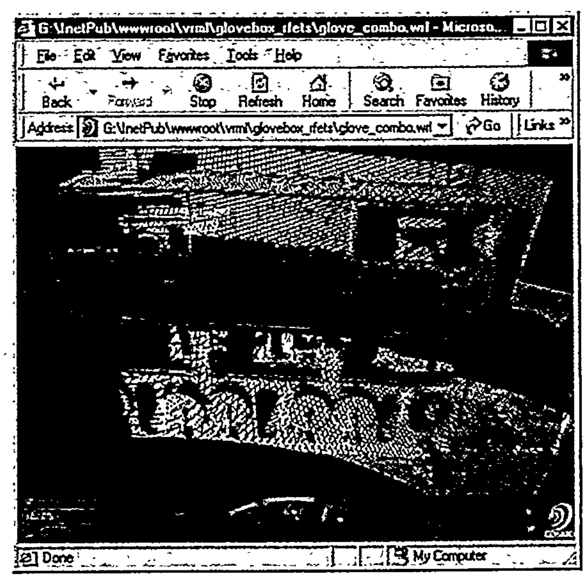


B. Robotic Laser Cutting of a Glovebox





D. Laser and Camera Mapping System



E. Rapid Model Building of a Glovebox

Figure 3. System Approach to Design

The second set of experiments tested the operational speed that the laser-mounted robot could size-reduce a typical RFETS glovebox. (The test gloveboxes were previously part of a production line in RFETS Building 771 that never went into hot operation.) In addition, experiments were performed to test the raw capability and throughput of a plasma torch deployed on a robotic arm, and to test the speed that existing rapid modeling hardware could automatically inspect and model a glovebox.

The photograph in Picture B of Figure 3 shows the operators controlling a robotic laser cutting system to size reduce a glovebox from Rocky Flats. The observed cutting speeds were 80 inches per minute for the laser system and 180 inches per minute for the plasma arc system. An analysis of a typical glovebox from the DOE complex indicates that reduction of a 4' x 6' x 8' glovebox to 50-pound pieces should require about 300 linear feet of cut. Accounting for the added time that the operator would need to choose a cut and enter the decision using the graphical user interface, the test results translate into a cutting time of about two hours for the laser and about one hour for the plasma arc cutter per glovebox.

From the beginning of the study to the date of the experiment, this project only required slightly more than three weeks. The key to the rapid integration of a complex robotic system with an experiment such as this one is the modeling and planning software (graphical programming and user interface [3] [4]) that was developed by Sandia National Laboratories. Picture C of Figure 3 shows how the operators used a rapidly constructed model of the glovebox, and then placed and simulated virtual cut paths for all major cuts to be performed. Within the simulation environment, these cut paths were represented as either a sequence of points, as virtual tape measurement tools, or as virtual cut parts.

The simplest way to define a cut path was to (1) load a virtual tape measurement object, (2) snap it onto the surface where the cut should originate, (3) rotate it as needed, and then (4) *scale* or virtually pull out the tape to indicate the length of the cut. In the image shown in Figure 3, three of these virtual tapes have been snapped to the glovebox to indicate short cuts.

For more complex paths, the operator can define cuts as a sequence of points. In the image in Figure 3, the two paths going around the glove/window areas were defined as free paths. In Picture C, the engineer *created* a path and click-created a path point on the surface of the box for each defining point along the path.

In addition, a rapid modeling experiment helped determine the extent an existing Laser Mapping System [6] (see Picture D of Figure 3) could automatically model an RFETS glovebox. The mapping system uses lasers with line generating optics and cameras mounted on computerized pan and tilt devices. Several laser/camera systems are used in combination. As the laser is panned across the object, the camera images the perspectively distorted line while software recreates the surface required to distort the line as imaged.

While laser mapping is a broadly used technology, Sandia's approach is unique in its ability to use multiple camera/laser systems. This allows the scanning of large and complex surfaces. The image in Picture E of Figure 3 shows the result of the scan. The three "stripes" show the model rendered as point data, fully textured mapped data, and simple polygonal data. Clicking on the image will load the actual model.

The second cutting experiments showed that laser robotic systems can efficiently size reduce gloveboxes within two hours for a typical 4'x 6'x 8' glovebox, and that plasma would further speed up the operation and allow for cutting a larger variety of parts. The modeling experiments showed that the inspection and generation of raw polygon models could be performed within minutes.

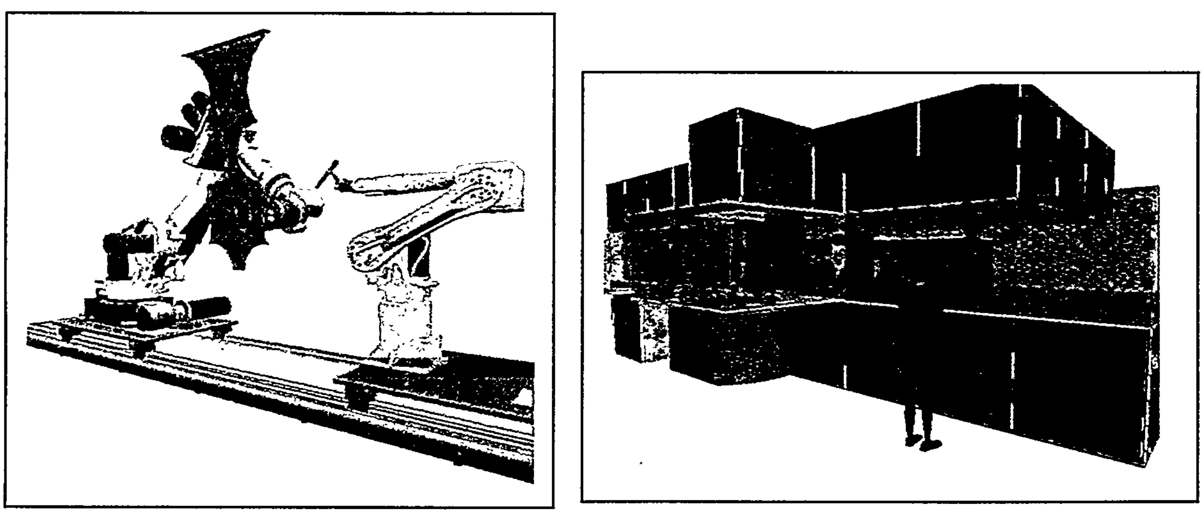
DESIGN RESULTS

Robotic System

The final design of the robotic system includes a special-purpose plasma-cutting robot subsystem and a general-purpose manipulation robot subsystem mounted on independent saddles on a common track.

The plasma-cutting subsystem can utilize a Fanuc M16iL, a Motoman SK16, a Motoman SK16M or an equivalent robot, a Hypertherm Max 200 plasma torch, and a Hypertherm CNC Torch Height Control (THC) unit. This subsystem is nearly a standard configuration for both Fanuc and Motoman (the exception being the inclusion of the THC unit). The THC may be eliminated if the robot servoing performance is determined to be adequate.

The manipulation subsystem can utilize a Fanuc 430iF, a Motoman UP130, or an equivalent robot, and be dressed with an automatic tool exchange device and several vendor-provided grippers. These grippers should include at a minimum, a vacuum gripper, a mechanical "hole and gloveport" gripper, and a general-purpose "EM-styled" gripper. In addition, the robot should be made easily adaptable to support a mechanical cutoff saw (such as the Sandia sawsall-based tool) and/or any additional devices whose need is identified through system testing or early system deployment. Drawing A in Figure 4 shows a design using two robots manufactured by Fanuc, integrated with a plasma cutter and mounted on a set of common rails.



A. Recommended Design

B. Integrated Robotic System inside a Permacon

Figure 4. Design Results

In addition, the manipulation robot should include sufficient sensing to allow it to perform simple "move react" or docking operations. In the past, Sandia has implemented this functionality with a JR3 force sensor and custom force sensing and servoing software. Fanuc is investigating whether its modern joint torque sensing software can provide this function without added hardware. Motoman recommends using proximity or other switch-based sensing. The final solution will hinge on the vendor chosen and follow a simple but detailed trade-off study between commercial and internally developed solutions.

Both robots should share a common rail but ride on separate saddles. The saddles should be robotically controlled and provided by the robot vendor. For hard-side deployment, this rail needs only be 4 meters long. For line 7, the rail would require a length of approximately 10 meters. Saddles might be reused between deployments.

It has been determined that the combined robot and rail systems have sufficient reach and dexterity to eliminate the need for adjusting robot height to cut the front, top, and bottom of the line 7 glovebox. In addition, the reach may be sufficient to allow the robot to cut the entire glovebox (including backside) from one setting. Further investigation is needed to validate this second observation and additional hardware or use approaches may be needed to cut the backside if this is found not to be true.

Control System

Industrial robots are typically used in repetitious operations where reprogramming of the robots is infrequent. However, remote operations that are needed in environmental remediation usually require the robot to perform a different task frequently. Therefore, the use of industrial robots necessitates the use of Sandia's graphical programming or its equivalent to reprogram the robot frequently. In addition, the industrial robots may need to add typical teleoperation inputs such as joysticks or spaceballs.

Whereas telerobots typically include button boxes to control joint-by-joint motion and spaceballs, joysticks, or mini-masters to provide coordinated motion, industrial robots use teach pendants for motion and programming. These teach pendants are typically sophisticated units that allow the user to move the robot in both joint-by-joint and straight-line fashions, as well as program the robot for industrial applications.

Thus, the manipulation robot may require limited telerobotic control interfacing software to allow it to be driven from a joystick, spaceball (6 DOF joystick), or other input device. Here, the need will be driven by the degree of RFETS user acceptance of standard teach pendants and the amount of "off normal" manipulation required. This feature should be implemented by Sandia if sufficient need is identified.

Sandia recommends porting its Sancho graphical programming software to a personal computer running Windows NT. The porting effort will address the important issues of software reliability and customization while building on lower-cost, easier to support computing platforms. This porting effort is also required to make Sancho directly compatible with the commercial robot's communications-based control packages. In addition to porting the software, Sandia must integrate the Sancho code with the commercial robot's communications-based control packages.

Modeling and Model Registration

Efficient use of graphical programming requires that appropriate geometric models be built and registered to the real world. The robot models will be a standard part of the control system and the robots' internal sensing systems will serve as the means for tracking their real motions in the simulated world. Key facility and equipment models will likewise be created once, but must be registered with respect to the robots. Glovebox and other cut-item models must be built for each glovebox being cut.

Sandia recommends using existing RFETS drawings and traditional as-built drafting techniques to build models of gloveboxes. Besides having sufficient accuracy, models built from drawings can better represent named features (e.g., glove ports) and can include internal structures that cannot be easily sensed (e.g., inner glovebox walls).

As operation pace accelerates, Sandia recommends gradual deployment of advanced automated modeling technologies to speed the building of glovebox models. Potential technologies include photogrammetry, laser mapping, and other 3D measurement techniques as well as emerging cloud to CAD data analysis techniques.

Sandia recommends using visual targeting as the primary means of registering glovebox models into the simulation environment. The visual targeting system should include the general methods for visual selection (i.e., operator carefully selects visual features, like corners, from video images) as well as automated methods for dot and key feature location (i.e., the system automatically finds the center of dots and glove ports from approximate selections). Finally, the visual targeting system should have the hardware capability for laser mapping to allow eventual incorporation of automated range-map to model registration. (Here, the cloud data is matched to the underlying model. Some model scaling may also be performed to provide real measurements of as-built conditions. In addition, the laser maps may be used to rapidly generate large scale models with modest accuracy.)

Sandia recommends that a system be developed to rapidly model unexpected or hidden features and accurately inspect important, but geometrically *tight* areas. Unexpected feature modeling should include generating models of areas that should be avoided as well as generating models of features that should be cut or otherwise worked on. Tight areas include, for example, places where high accuracy is required to keep the robot from crashing the torch into a gloveport while negotiating a critical cut. These features and areas are expected to be relatively small and only visible from specific vantages. The importance of this capability is expected to grow in proportion to the complexity of the boxes being size reduced and the acceptability of human (hands on) intervention.

To address this need, Sandia recommends development of a robot-held range scanning system. This system would likely utilize a camera and laser with line-generating optics, and leverage the laser mapping software used for registration and large scale model generation. Users would deploy the system by programming the robot to move in a scanning motion above the area of interest. Data gathered would be compressed and loaded into the simulation environment as a geometric *skin*. This skin would then provide a collision boundary or work area for specific work functions. Finally, Sandia recommends that this system be deployed in later project phases so that the needs can be fully bounded through operational experience.

Integrated System (see Drawing B of Figure 4)

Sandia recommends implementing the integrated robotic size reduction system in two phases. The first phase system would be deployed within a hard-side facility. Initially, the system would include two industrial robots on a single rail, standard and custom tooling, and Sandia-developed registration, modeling and control systems. Sandia also recommends that this system be operationally tested in cold and then hot facilities and progressively modified through tool and software approaches to achieve a 100% remote operational status.

The second phase system would be redeployed for in-situ remediation. Here, Sandia recommends redeploying the robots, tooling, and software and purchasing new rails and possibly rail positioning hardware.

Training

Sandia recommends that RFETS identify and work with Sandia to develop the needed skill base to utilize the proposed system. Due to the unique nature of this system, the following new skills need to be developed to fill new work functions.

Graphical programming and robot modeling: All robot operators must become familiar with the basic modeling and control system. Personnel preparing models should have a stronger ability to manipulate the models while those using the robot need a basic understanding of CAD modeling and using CAD models.

Robot Operation: Operating robots requires a similar skill set to operating standard industrial computer-controlled machines like the numerically-controlled milling machines found at RFETS. Operators should have a strong mechanical aptitude, a careful nature, and be willing to learn the computer controls that the machine uses. A key ability is to visualize or understand the basic "how and why" of machine motions and actions.

Recommended prerequisite skills include:

- Modest proficiency in Windows NT.
- CAD experience (3D modeling preferred).

The following training experiences should be utilized:

- IGRIP training from Deneb (1 week minimum plus 4 weeks learning curve. Highest proficiency needed for glovebox modeling).
- Sancho operator interface training by Sandia. Prerequisite IGRIP training.
- Robot user training from robot system vendor.
- High mechanical aptitude (understanding and ability to properly use tools and visualize motions).
- High aptitude in radiological hazards and the size reduction process.

Supervision and Customization: One or more operators should be trained as a system supervisor or key operator. Background requirements include:

- Limited programming background (Tcl/Tk preferred, but basic programming provides an acceptable base).

- Windows NT system configuration (i.e., ability to install and maintain programs and computer).
- Internet skills (ability to download program updates from Sandia).
- Service training from robot vendor.
- Operator skills mentioned above.

SIMULATION RESULTS

A simulation was performed showing the reach capabilities of the proposed robots when placed within the RFETS-proposed hard-side facility in room 149. The simulation validates the extent to which robots can reach the various important portions of typical (4' x 6' x 8') gloveboxes. While this simulation uses Fanuc robots, equivalent commercial machines may be substituted after performing a similar analysis. If desired, the robot can be programmed to remove lead on the surface of the stainless steel using mechanical means, so as to eliminate the hazard of vaporizing lead, perform a tool change, and complete the cut using the laser or plasma cutter.

The simulation includes the following steps:

1. The glovebox is brought into the room.
   - Handling equipment (not included in this design) could consist of a simple remote operated crane on a guide rail.
   - The room layout should be adjusted to provide a more direct path for the glovebox while still allowing the robots to work near the waste box. A similar rearrangement would also benefit manual operations were the robots not used.
2. The robots move along the rail to approach the first cut location.
   - Cuts would be similar to those proposed for Line 7.
   - The robot's height, relative to the boxes, could be adjusted to allow the robots to cut from the top pointing down, rather than cut from within and pointing upwards.
   - Back walls would be cut from the inside, pointing out.

Similarly, a second simulation was performed for in-situ size reduction of the Fluorinater Lines. The simulation shows the basic process for cutting the Line 7 glovebox with the proposed two-robot system. The simulation indicated the extent to which the robots can reach the various important portions of the Line 7 glovebox and explores a new concept for performing the cut schedule. While this simulation uses Fanuc robots, equivalent commercial machines may be substituted after performing a similar analysis.

The simulation includes the following steps:

1. A piece is cut from the outer water wall.
   - The cutting robot cuts a hole that the other robot can use as a grip point.
   - The robot cuts along the first three sides, trying to remove as much material as possible.
   - The manipulation robot grabs the plate at the previously cut hole and pulls slightly to assure that the piece does not fall behind the wall.

- The cutting robot finishes the cut and moves away.
- The manipulation robot carries the part to the standard waste box.
- After the piece is cut, the outer water wall turns invisible to show that this process would be repeated for the entire side of the glovebox.

2. A piece is cut from the inner water wall.
   - Again, the cutting robot cuts three sides of the plate as well as a grabbing hole for the other robot. This time, collision avoidance algorithms successfully avoid the scrap material left from the first cut.
   - The manipulation robot again grabs the part and lets the cutting robot finish the cut.
   - The inner water wall disappears to show that it would be removed.
3. The interior wall is cut.
   - Rather than cutting between the glove ports, this cut travels around the glove ports.
   - Also, rather than making a gripping hole, the manipulation robot holds a glove port. Here, a different surface is used on the original gripper to tightly hold this standard feature.
   - Finally, the inner wall disappears to show that it would be removed.
4. The robot moves along the glovebox roof as if to cut pieces from the inside. Such cuts limit the height requirements for the system, and optimize tool geometry to provide sufficient reach throughout the process.
   - Further study is needed to validate whether cuts can be made from the inside surface working out. The primary concern is whether obstacles will interfere with the cutting. A secondary concern is the direction that the sparks would travel.
   - Further study is needed to optimize tool geometry and robot placement to assure that the robot has sufficient reach.
5. The robot moves along the back wall of the glovebox as if to cut pieces from the inside out.
   - Issues pertaining to Step 4 apply here.
   - Cuts made on the inner surface are similar to those on the outer wall.
   - Cuts made on the inner water wall are similar to those made earlier. Different cut plans are made for areas not covered by a third water wall.
   - Cuts made on the outer water wall are similar, but more complex than the inner earlier inner wall cuts.

CONCLUSION

The simulations and experiments reported in this paper show that the application of commercially available industrial robots for environmental restoration is viable. The design makes use of commercially available robots that are used in the automotive industry. The commercially available industrial robots provide high reliability and availability that are required for environmental remediation in the DOE complex. The costs of commercial robots are about one-fourth that of the custom made robots for environmental remediation. The reason for the lower costs and the higher reliability is that there are thousands of commercial robots made annually whereas there are only a few custom robots made for environmental remediation every year. In addition, advanced application of robotic controls over the Internet is possible in unique applications. This was demonstrated in the DOE Robotics Technology Development Program Forum in 1994 and 1996 [5].

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