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Office of Environmental Restoration and Waste Management
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Robotics Technology Development Program**

Lawrence Livermore National Laboratory

**Summary of LLNL's Accomplishments
for the
FY93 Waste Processing Operations Program***

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DOE 1993 Waste Processing Operations Program Participants

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EXECUTIVE SUMMARY

Objective: Develop Technology to Improve Handling of DOE's Mixed Waste

Currently, primary methods of handling and processing heterogeneous mixed wastes are conducted by operators in fully protective suits, working within containment systems. These operations involve risks to the safety and health of operators and excessive generation of secondary processing wastes. Furthermore, current methods are costly, time consuming, and have a high potential for human error. Also, environmental and personnel safety and health regulations governing hazardous materials and wastes are increasingly more stringent and difficult to meet. The U.S. Department of Energy's (DOE's) Office of Technology Development (OTD) is charged with the development of innovative waste treatment technologies to overcome the shortcomings of current methods of handling DOE's mixed, low-level, and transuranic wastes.

LLNL's FY93 WPO Program Work Substantially Advanced Robotics and Automated Handling of Mixed Wastes

Working under OTD's FY93 Waste Processing Operations (WPO) Program, and in concert with other contributing National Laboratory WPO Team members, Lawrence Livermore National Laboratory's (LLNL's) Environmental Restoration and Waste Management Program (ER&WM), made substantial progress toward developing automation and robotics technologies for heterogeneous mixed waste handling and processing. LLNL's technical tasks focused on developing key enabling technologies and integrating them into a baseline prototypical mixed waste handling system. Important advances were made in all key technology areas: nondestructive evaluation of storage drums using computed tomography; mixed waste singulation with automated grasp planning; waste characterization and segregation with fixed sensor arrays and advanced decision making algorithms; autonomous and teleoperated waste processing using surface decontamination with scarifying technology; and integration of multiple tasks with a state-of-the-art supervisory control system.

The MWO Demonstration Showcased State-of-the-Art Technology for Improved Handling of DOE's Mixed Wastes

The LLNL prototypical integrated mixed waste handling system was successfully demonstrated as part of DOE's Mixed Waste Operations (MWO) Demonstration at Savannah River Technology Center (SRTC) on November 2-4, 1993. The WPO Program Team participating in the MWO Demonstration consisted of experts from LLNL, Oak Ridge National Laboratory, Sandia National Laboratories, and SRTC. The DOE MWO Demonstration showcased state-of-the-art automation and robotics technology applied in an integrated fashion to handling of heterogeneous waste. It provided a viable system for future development of remote handling and characterization systems for hazardous waste. The MWO Demonstration fostered interest on the part of DOE, industry, and universities in participating in development of similar equipment for future, worldwide waste cleanup efforts. Thus, the objective of making future DOE mixed waste handling facilities better, faster, safer, and more cost effective is an important step closer to realization.

1.0 INTRODUCTION

Under the U.S. Department of Energy's (DOE's) Office of Technology Development (OTD)-Robotic Technology Development Program (RTDP), the Waste Processing Operations (WPO) Program was initiated in FY92 to address the development of automated material handling and automated chemical and physical processing systems for mixed wastes. The WPO Program Team was led by LLNL and composed of experts from four national laboratories: Lawrence Livermore National Laboratory (LLNL), Oak Ridge National Laboratory (ORNL), Sandia National Laboratories (SNL), and Savannah River Technology Center (SRTC). The WPO Program focused largely on responding to the needs of DOE's Mixed Waste National Program. The Program's mission was to develop a strategy for the treatment of all DOE mixed, low-level, and transuranic wastes. As part of this mission, DOE's Mixed Waste Integrated Program (MWIP) was charged with the development of innovative waste treatment technologies to surmount shortcomings of existing baseline systems. Current technology advancements and applications result from cooperation of private industry, educational institutions, and several national laboratories operated for DOE.

By incorporating automated material handling and automated treatment processes into mixed waste facilities, a number of benefits that support DOE's goals of faster, safer, better, and cheaper waste processing are potentially realized. Benefits include the following:

- Improved safety with reduced operator exposure to radiation and handling hazards

- Improved efficiency in handling and processing wastes
- Improved control and documentation of operations
- Reduced risks to the worker, the public, and the environment
- Reduced requirements for personnel and facilities
- Reduced secondary waste generation from protective clothing
- Reduced costs of treatment, recycling, and disposal of hazardous wastes.

In FY92 and FY93, the WPO Program Team emphasized automated material handling, *in situ* and in line characterization, segregation of incoming waste, and treatment of a candidate waste stream. This emphasis supports improvement of productivity, reduction of process wastes, and minimization of operator hazards.

This summary document presents the LLNL Environmental Restoration and Waste Management (ER&WM) Automation and Robotics Section's contributions in support of DOE's FY93 WPO Program. This document further describes the technological developments that were integrated in the 1993 Mixed Waste Operations (MWO) Demonstration held at SRTC in November 1993.

2.0 SCOPE OF LLNL'S FY93 WPO WORK

LLNL's FY93 WPO project tasks focused on the development of selected key enabling technologies required to automate the handling and processing of heterogeneous mixed waste. The technical project tasks were the following:

- **Nondestructive evaluation (NDE)** of whole drums and waste stream objects using **computed tomography (CT)**
- **Mixed waste singulation** (separation of multiple objects from a pile or drum into individual, easily characterized packages), with object characterization and automated grasp planning
- **Waste characterization and segregation** with fixed sensor arrays, automated sub-systems, and advanced decision making algorithms to quickly and accurately determine object properties for sorting
- **Waste processing** (surface decontamination) using scarifying technology and autonomous inspection of homogeneous metal objects
- **Integration of multiple tasks with a supervisory control system** with the flexibility of shared control between the operator and the automated systems.

LLNL expertise was drawn from the Engineering Science Division (ESD) for non-destructive characterization technologies; from the Engineering Research (ERD) Division for advanced vision and imaging technology; and from the ER&WM Section for advanced robotics and supervisory control technologies. Technologies from these different LLNL organizations were initially developed and demonstrated as stand alone technologies in FY92.

Throughout FY93, these technologies were further developed and integrated as a baseline prototype waste handling system to demonstrate the advantages of automation technology as a potential solution to the heterogeneous mixed waste problem.

During the fall of 1993, this LLNL baseline prototypical integrated mixed waste handling system was deployed to SRTC and demonstrated as part of DOE's MWO Demonstration on November 2-4, 1993. Figure 2-1 shows the flow of waste through the integrated system at the MWO Demonstration: non-destructive evaluation of drums and waste objects; waste singulation (separation of multiple objects from a pile or drum into individual, easily characterized packages); waste characterization and segregation; and waste processing and treatment, integrated into a coherent mixed waste handling and treatment system prototype under computer supervisory control.

The MWO Demonstration at SRTC had several specific objectives. First, the MWO Demonstration was intended to showcase automated and robotic systems operating in a coordinated manner beginning with front-end waste stream characterization and handling activities through to a candidate waste treatment process. Second, the MWO Demonstration was intended to emphasize the feasibility and advantages of automation and robotics technologies applied specifically to mixed waste material handling and processing. Third, the MWO Demonstration was intended to provide a conceptual picture to DOE constituents, potential industrial partners, and university researchers. Although not expected to provide robust or all-encompassing technologies, the MWO Demonstration showcased state-of-the-art robotic technology applied in an integrated fashion to handle heterogeneous solid wastes.

2.0 SCOPE OF LLNL'S FY93 WPO WORK

Figure 2-1. Flow of waste through the integrated system at the MWO Demonstration.

3.0 SUMMARY OF ACCOMPLISHMENTS

This section summarizes LLNL's technical task accomplishments carried out under the auspices of DOE's FY93 WPO Program. Significant technical developments were achieved that lay the foundation for achieving the goal of automating the handling and processing of heterogeneous mixed waste. Detailed descriptions of the underlying technology are provided in Section 4.0.

Computed Tomography Non Destructive Evaluation of Drums and Waste Objects

Computed tomography technological development is targeted at both present and future DOE sites that require onsite capability to certify newly generated waste drums in accordance with Federal standards. DOE sites must examine, reprocess, and repackage waste drums stored onsite in aboveground or buried containers. Before opening or shipment after repackaging, containers must be labeled, assayed, and certified. The assay results determine ultimate disposition of the waste containers. An accurate, non-destructive assay method identifies all radioisotopes present and provides a quantitative measurement of radioisotope activity in the drum. With computed tomography, waste containers are routed cost effectively without reopening.

Because of size and safety constraints, computed tomography technological development for whole drum characterization was conducted at LLNL before the MWO Demonstration. Specific technical tasks accomplished included the following:

- Completion of non-invasive waste drum analysis and determination of quantitative data (such as radioisotopes and metal homogeneity) for waste stream objects
- Coupling of object data into the waste stream segregation algorithms as part of the sensory data set
- Coupling of computer data reduction and interpretation with three dimensional (3-D) graphics displays to render the data in a more understandable format for the operator
- Representation of whole drum characterization data in video and presentation format for the MWO Demonstration.

Active and passive computed tomography measurements using energy-dispersive detection systems may significantly improve the assay of radioactive wastes. Experimental results reveal that the non-destructive assay, active and passive computed tomography techniques can be used to apply active computed tomography data to correct experimental passive computed tomography data. Whole drum characterization data were represented in a 3-D video tape for presentation at the MWO Demonstration.

Waste Singulation Using Structured Lighting-Based Object Characterization and Automated Grasp Planning

Typical autonomous robot grasping approaches are useful primarily when objects are known and unvarying. In hazardous waste sorting, grasping is more difficult because objects are unknown and often are wrapped in plastic bags. Therefore, a more general approach is required when the grasp pose is computed automatically for the unknown object. Autonomous grasp planning technology computes and recommends grasp poses based on the structured lighting system geometry interpretation and known grasping rules and configurations. Grasp orientation of the object with respect to the end-effector is determined by scanning the gripper. This process permits precise manipulations of objects without fixtured grasps.

LLNL developed and demonstrated algorithms for singulation of objects from a pile, using the LLNL Puma 562 robot. For the formal MWO Demonstration, a 762 Puma robot supplied by SNL was used as a teleoperated robotics system to perform singulation of waste objects. Waste stream objects were successfully placed, using a combination of teleoperations and autonomous robot programming.

The successful merging of two important software development "tools" for robotics control, (the SNL-developed GENISAS software integrated with high level supervisory control through CIMETRIX, with Robline software) was a significant accomplishment. As a result, all future software developments and system integration efforts will be simplified significantly.

3.0 SUMMARY OF ACCOMPLISHMENTS

Successful integration of the seamless transfer capabilities allowed systems to run smoothly in autonomous mode; transition to teleoperational mode to allow operator intervention if an error condition occurred; and transition back to autonomous mode once the error condition was corrected or the operator provided higher level decisionmaking.

Although the structured lighting system was not integrated for the formal MWO Demonstration, the algorithms necessary to calculate a valid grasp from the 3-D structured lighting data were fully developed and tested in FY93. At LLNL in December, 1994, the ORNL structured lighting system was integrated with LLNL's grasping algorithms to successfully execute automated grasping from a drum filled with objects.

Waste Characterization and Segregation System

Metal segregation, particularly of metals that can cause damage during waste processing, is an important step in the feed preparation process. LLNL purchased and integrated a commercial production-line metal detection system capable of measuring ferrous, non-ferrous, and stainless steel metals in the waste stream. This system was integrated with an array of other sensory systems.

A rapid, reliable, and efficient method for sorting dry, heterogeneous waste was designed, implemented, and tested. The waste characterization system was installed and tested at LLNL prior to shipment and installation at SRTC for the MWO Demonstration.

The dry, heterogeneous waste was characterized nonintrusively by conveying it through a sensor system that measured the physical properties of the waste. A metal detector was used to determine if any significant metal existed in the object and the approximate size of the metal. A sodium iodide (NaI) detector was used to determine if there was a significant amount of radioactive material. Data from force sensors and a profile detector were used to calculate approximate density.

For the MWO Demonstration, X-ray gauge data previously taken at LLNL were applied to determine variations in material density. This information

about the physical characteristics of the waste was put into a fuzzy logic algorithm designed to determine the appropriate treatment line for the object. Waste stream objects were classified into the appropriate treatment line based on material type, radiation signature, special handling requirements, and basic object geometric data such as size, shape, and volume. This activity facilitated evaluation of the sensitivity, throughput, and adaptability of the metal detection system as a metal discrimination device. Metal discrimination for separation of many ferrous and nonferrous metals was performed with magnetic and paramagnetic sorting techniques. A study was completed demonstrating how an industrial metal detector could be used for metal discrimination.

Waste Processing/Surface Cleaning and Scarifying System

Reuse or recycling from waste streams of stainless steel and other valued metals is economically desirable because of disposal and storage costs and the value of the materials. Lead is used in large quantities throughout the DOE Complex, and becomes radioactively-contaminated. Radioactively-contaminated lead is a high profile mixed waste with few disposal options. Surface cleaning and scarifying allows separation of the hazardous and radioactive components from lead, stainless steel, and other valued metals for easier disposal and possible material reuse. Decontamination and surface cleaning are potential procedures to be performed by robotic operation as tasks that are labor intensive, tedious, and potentially risky to operators.

In a glovebox processing system, LLNL developed and demonstrated autonomous and teleoperated surface decontamination with scarifying technology for treatment of radioactively contaminated metals. Surrogates were used to avoid generation of mixed wastes during technology development. The scarifying technology was demonstrated using CO₂ pellets as the cleaning medium for homogenous metals.

Automated cleaning of easily characterized geometries (bricks) was performed in FY93, along with teleoperated cleaning of complex shapes (bent lead sheeting). The teleoperational and autonomous

3.0 SUMMARY OF ACCOMPLISHMENTS

grasping of objects, scarifying of metal objects, and inspection of cleaned objects all were successfully demonstrated.

Region-based collision avoidance was used throughout LLNL's MWO Demonstration. Movements of the robot from region to region were made without collision, independent of position after teleoperations.

Development of technologies for inspection of complex shapes, collision avoidance, and more complicated grasp planning is progressing in 1994.

Supervisory Control System (SCS)

An integrated supervisory control system was developed to successfully allow an operator using a single user interface to control the multiple process systems: mixed waste-handling, characterization, and processing tasks. LLNL, with ORNL and SNL, provided hardware and SRTC provided onsite support at the MWO Demonstration to integrate the processing and feedstream handling systems. Control and monitoring of the multiple process systems was demonstrated with a supervisory controller with the flexibility of shared control between the operator and the automated systems.

The SCS, designed and developed for the integrated system, incorporates advanced technologies including an event-driven finite state machine for multiple processes and the independent menu manager process. Prior research facilitated development of system control with finite state machines. Traditional finite state machines were advanced from a sequentially-driven transition machine, to a stochastically-driven transition

machine. The SCS incorporates "indeterminate" event delivery to multiple processes, while maintaining the ability to perform sequentially driven tasks.

The menu management facility of the SCS is a unique, innovative X-Windows application. The menu facility operates as a separate process in a multi-purpose environment and responds to event-driven requests and information. Traditionally, graphical user interface (GUI) facilities were integrated into the application package. Based on the LLNL innovative approach, the menu manager as an independent process allows the applications to be performed more efficiently and more directly with Robline. The menu manager for the MWO Demonstration required a unique X-Window applications loop to poll the X-Window display inputs and the event-driven request.

Formal MWO Demonstration

The formal MWO Demonstration was an excellent showcase for development and integration of LLNL's technologies. The MWO Demonstration provided the opportunity for identification of prominent issues and significant problems for new automated mixed waste handling techniques. Technologies were proven and areas of future essential development were revealed. The feasibility of automated and robotics handling of wastes was demonstrated in a manner that provided a benchmark or baseline of technology. The MWO Demonstration not only allowed technical experts to gain understanding of some fundamental issues, but also provided a conceptual picture for DOE staff who can provide continued funding toward achievement of the technical solutions.

4.0 KEY ENABLING TECHNOLOGICAL DEVELOPMENTS

4.1 COMPUTED TOMOGRAPHY NONDESTRUCTIVE EVALUATION OF DRUMS AND WASTE OBJECTS

4.1.1 Introduction

Many mixed waste containers are old and content descriptions are vague, questionable, or unknown. Before mixed waste containers enter a facility, knowledge of types and quantities of contained material is essential. This information confirms whether the container is acceptable for processing in the facility. Furthermore, the information allows better planning for treatment of waste and assures continuous supply of feed stock to the different treatment processes.

Computed tomography (CT) technology development is targeted at both present and future DOE sites. These sites will require onsite capability to certify newly generated waste drums in accordance with Federal standards. Waste drums stored onsite in aboveground or buried containers must be examined, reprocessed, and repackaged. Prior to opening and prior to shipment after repackaging, containers must be labeled, assayed, and certified; assay values determine the ultimate disposition of waste containers. An accurate non-destructive assay method using active and passive computed tomography (A&PCT) can identify all the radioisotopes present and provide a quantitative measurement of radioisotopic activity in the drum. In this way, waste containers can be routed most cost effectively without reopening. Because of the large size of CT scanners and safety constraints relating to high energy x- and gamma-ray sources, CT technology development was conducted only at the LLNL site and the CT scanners were not deployed to the MWO Demonstration at SRTC.

4.1.2 Objectives

The objective for use of CT was to conduct non-destructive evaluation of drums and waste objects. For the MWO Demonstration, waste drum analyses and quantitative data (such as radioisotopes present and determination of metal homogeneity) of waste stream objects were provided from LLNL. Although the actual CT scanners were not deployed to SRTC, the information gathered was to be applied. The whole drum characterization data were represented at the MWO Demonstration in video and presentation format, while the information and data on the actual object

were coupled into the waste stream segregation algorithms as part of the sensory data sets. The CT computer data reduction and interpretation processes at the MWO Demonstration, coupled with 3-D graphics displays, were designed to render the data in an understandable format to the operator.

4.1.3 Technical Approach

Imaging by conventional x- and gamma-ray CT measures the effect of an object on an incident beam or ray that travels in a straight path. Data measured are photon intensities of the incident beam and the transmitted beam that are attenuated by the object. The incident beam is partially absorbed and scattered in the object of interest, with remaining transmitted photons traveling in straight lines to the detector where the photons are recorded. The quantity recorded at each x, y coordinate of the detector plane provides the digitized radiographic image of the object. These radiographs or projections are recorded at many different angles around the object. Using these projections, the internal structure of the object is reconstructed by computer. The reconstructed quantity is the attenuation value for a volume element, or "voxel," at location x, y , or z within the object. The voxel size and clarity are defined by scan and image reconstruction parameters. The reconstruction algorithms require line integrals or ray sums, for many ray paths through the object. Each ray sum is recorded at each individual x, y detector element at different angles around the object. The CT ray sum, acquired at a single energy, is analogous to a simple gamma-ray transmission gauge.

A&PCT is a comprehensive and accurate gamma-ray non-destructive assay (NDA) method that can identify all detectable radioisotopes present in a container and provide a quantitative measure of activity. Active CT technology can yield quantitative attenuation data (related to density and atomic number) for the waste matrix within a drum. Passive CT technology localizes all detectable radioisotopes within a drum and can accurately determine the identity from the energy spectrum generated by the isotope. For active CT, the function to be imaged is the measured x- or gamma-ray attenuation of an object using an external source; whereas, in the case of passive CT, the function to be imaged is the measured gamma-ray activity, at one or more energies, of all detectable radioisotopes within a drum. Active CT images are used to correct the passive

4.0 KEY ENABLING TECHNOLOGICAL DEVELOPMENTS

CT images for attenuation to accurately determine the activity of the internal emitting source. For an A&PCT scanner with gamma-ray spectrometry detection equipment, each radioisotope in the drum can be identified by the energy of characteristic peaks.

For the MWO Demonstration, A&PCT scans were acquired on a 55-gallon drum filled with mock waste items and a radioactive emission source. The mock waste consisted of three plastic bags filled with paper, glass, and metal to represent waste at LLNL and other DOE sites. These bags were placed inside the drum at the same height. A ^{133}Ba radioisotope sealed source was placed within the waste matrix to represent the passive radioactive source inside the drum. This source was positioned between the glass (Figure 4-1) and metal bags. A series of data sets were acquired. Each set consisted of two passive and one active scan. One passive CT scan was used as a reference (without drum or waste as attenuators). The second passive CT scan and the active scan were obtained on the drum at the same location with mock waste and the passive ^{133}Ba source. These data sets were used as follows:

- Active CT data to obtain images that represent cross-sectional attenuation maps of a waste canister's contents
- Passive CT data to locate and determine the identity of any radioisotopic sources present
- Active CT data to correct the passive CT data to facilitate accurate source strengths.

Representative A&PCT results are shown in Figure 4-2. With data analysis, the summed activity value of the reference active CT image (Figure 4-2a) is compared to the summed activity value of both attenuated passive CT images (Figure 4-2b and 4-2d). Results reveal that the uncorrected passive CT (Figure 4-2c) summed activity value is 45% lower than the reference value. As the attenuation by the drum and mock waste was not considered, the activity value was anticipated. The passive CT image corrected for attenuation (Figure 4-2d) yielded a summed activity value 10% higher than the reference value. The attenuation-corrected passive CT summed activity value was closer to the reference value, as anticipated. However, the ~10% overcorrection was not clear. This error probably resulted from the assumption of parallel beam geometry for the passive CT reconstructions.

Currently, development and tasking of reconstruction algorithms that properly account for errors due to geometrical effects is progressing. These preliminary A&PCT scan results reveal that passive CT can localize and identify internal radioactive isotopes; and that active CT scans properly map the canister's attenuating matrix such that, when coupled with passive CT scans, more accurate passive source activity values result. The whole drum characterization data was rendered in 3-D and presented on a video tape for the MWO Demonstration.

Both integrating and nuclear-spectroscopy (pulse mode) CT scanners were used to characterize various individual mock-waste items that are representative of DOE waste streams (that is, metals, combustibles, organics, mixed, and radioactive). Methods were investigated to optimize the characterization of these items and minimize scan time. 2-D attenuation maps of several representative waste items were reconstructed to determine whether the items contained homogeneous or heterogeneous metal, and radioactive, combustible, or unknown materials. Experimental CT results were compared to theoretically predicted values to identify the materials. Data were successfully used at the MWO Demonstration to render the information in a more understandable format to the operator. The actual object data was coupled into the waste stream segregation algorithms as part of the data set.

One of the scanners incorporated a well-collimated single source (isotopic or x-ray tube) and a single, nuclear-spectroscopy-based detector. Each data point (or pixel) in the reconstructed images produced from this scanner represented the linear attenuation coefficient for a particular volume element within the object under inspection. This was the same value provided in tables of cross sections. Experimental CT results were compared to theoretically predicted values to identify materials; no additional measurements were required. Furthermore, ratios and differences of CT reconstructed images taken at different energies were reduced to functions used to calculate the material properties for each voxel. Figure 4-3 and 4-4 show CT reconstructed images at 317 keV and reveal information about types and quantities of materials within a motor system. This data was coupled into the waste stream segregation algorithms as part of the sensory data set. (Section 4.3 discusses waste characterization and segregation). The computer data reduction and interpretation, coupled with 3-D graphics displays, are

4.0 KEY ENABLING TECHNOLOGICAL DEVELOPMENTS

Figure 4-1. PCT scans were acquired on a 55-gallon drum filled with mock waste items and a radioactive emission source.

4.0 KEY ENABLING TECHNOLOGICAL DEVELOPMENTS

Figure 4-2. Representative reconstructed active CT (a) and passive CT (b-d) images of the full size 55-gallon simulated waste drum. For the active CT image, the colorbar (a, bottom) provides a scale relating the different gray shades in the CT image to the linear attenuation coefficient in cm^{-1} . The attenuation variations are related to changes in density (ρ) and/or effective-atomic number (Z_{eff}). For passive CT images, the colorbar represents the photon counts accumulated at each pixel during the integration period.

4.0 KEY ENABLING TECHNOLOGICAL DEVELOPMENTS

Figure 4-3. (a) Representative CT image of a DC motor. The colorbar below the image provides a scale relating the different shades of gray in the CT image to the linear attenuation coefficient in cm^{-1} . The attenuation variations are related to changes in density (ρ) and/or effective-atomic number (Z_{eff}). (b) A 1D profile (black line) through the CT image shows the variation of the linear attenuation coefficient within the motor. The measured attenuation coefficient is compared to theoretically calculated values of various materials (labeled and shown by various flat lines). This enables us to determine whether the imaged item contains homogeneous or heterogeneous metals and/or radioactive, combustible, or unknown materials.

Figure 4-4. A histogram of the CT image can be used to identify materials within the individual waste item and indicate relative amounts. If the histogram contained only two peaks, one for background (air) and one for steel, the item would be classified as a homogeneous metal. However, the histogram of this CT image contains many peaks and indicates the presence of heterogeneous metals.

4.0 KEY ENABLING TECHNOLOGICAL DEVELOPMENTS

used to render the data in a more understandable format to the operator. Types of material were color coded in the 3-D display to provide an easily interpreted representation of the data.

4.1.4 Future Developments

Depending on the resolution and accuracy desired, CT can take hours for data acquisition and reconstruction. However, techniques and equipment modifications are under investigation to speed the process without reduction in resolution or accuracy. Further experiments are continuing to investigate the A&PCT results; to fully understand the propagation of errors within the reconstruction codes; and to better understand optimum methods for both data acquisition and image reconstruction. Future work will include the incorporation of CT data into ER&WM waste sorting/characterization algorithms.

4.1.5 Summary of Accomplishments

Extensive CT was completed on whole waste drums for characterization and analyses and on waste stream items for object characterization. The specific technical tasks included completing nondestructive analyses of a whole waste drum and individual waste stream objects to determine quantitative information regarding radioisotopes, and to determine metal homogeneity.

A&PCT measurements using energy-dispersive detection systems have the potential of significantly, nonintrusively improving the assay of radioactive wastes. The experimental results revealed that the NDA A&PCT technique can be applied to active CT data to correct the experimental passive CT data for attenuation by heterogeneous-waste matrices as long as nearly parallel-beam active CT and passive CT data are recorded. The whole drum characterization data was represented in a 3-D video tape for presentation at the MWO Demonstration.

4.2 WASTE SINGULATION

4.2.1 Introduction

Singulation is the process of separating and sorting individual waste items from a container or pile. Manual removal of waste items directly from a drum exposes personnel to radiation and hazardous material, and to the possibility of cuts and punctures from sharp items.

Manual removal requires extended reach to the bottom of the drum to remove heavy and bulky items. Hazards from these operations can be reduced by dumping material from the drum, but then knowledge of orientation and position of specific waste items identified during whole drum characterization is lost. Manual removal by reaching or dumping requires exposure and presents safety risks. Any cuts or wounds to operating personnel are potentially contaminated. Remote removal and placement of individual waste items reduces risk to personnel, increases throughput, and reduces secondary waste generated from essential use of personal protective equipment. Successful remote singulation directly from drums and from a pile dumped from a previously opened drum was performed at the MWO Demonstration.

4.2.2 Objectives

For the MWO Demonstration, the "singulation" process was performed on the waste items to facilitate waste characterization and waste treatment. The main task objective was to separate waste objects from both a pile and a waste drum into quantities more easily characterized. This procedure was performed in both autonomous and teleoperational mode. Integral to performance of singulation in autonomous mode was the development of a software algorithm for autonomous grasp manipulations. This grasping algorithm accepted 3-D data regarding the waste stream items and determined optimal grasp points on the objects and the appropriate gripper for the grasping process. The actual task of singulation was executed using a Puma 76? robot. The source of 3-D data for the grasping algorithm was a structured lighting source, developed at and supplied by ORNL.

Another technical objective was to determine approximate object weight after each object was in the grasp of the robot. The approximate weight was determined using the JR3 forces/torque sensor. This data combined with volumetric data was to be passed to the waste characterization process system to aid in identifying material properties of the objects.

Because of the unstructured and constantly changing environment, some tasks required teleoperational manipulations and operator decision-making capabilities. As an example, the operator was required to perform corrective actions to recover from error conditions. The software/ hardware control systems

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were required to have the ability to perform transfers between autonomous and teleoperational mode in a seamless manner, with little or no special preparation between mode switching. In the teleoperational mode, a 6 DOF force ball was used as the input device.

Late arrival of the portable structured lighting hardware prevented reliable integration of the autonomous grasping sub-system as part of the waste singulation process. However, robust and reliable singulation was successfully performed in the teleoperational mode of control for the formal MWO Demonstration.

4.2.3 Technical Approach

The singulation system uses a PUMA robot with a payload of approximately 40 pounds. A JR3 force sensor is attached to the robot's wrist and a Robohand tool changer allows use of various end effectors. Robline provides a graphical operator interface and generates all the commands for autonomous operations (such as object placement and tool changeouts). For teleoperation, an interface was developed by SNL, using a GISC-compatible software module called SMART (Sequential Modular Architecture for Robotics and Teleoperation). SMART facilitates use of different master input devices for teleoperation. A Dimension 6 force ball by CIS is used to manipulate the PUMA. This device is directed by the operator to remotely control the PUMA robot, using cameras to assist in locating the objects.

The force sensor is managed through the SMART software to prevent excessive force development during singulation. Excessive force could damage the robot, the waste items, or surrounding equipment. Figure 4-5 illustrates the singulation system hardware.

To control the singulation robot for autonomous tasks, software interfaces the high level graphical simulation and control side with the low-level control side. The software for both ends was written to use libraries and protocols of the GENISAS communications architecture developed by SNL.

This protocol isolates the operator/programmer from the transport, the hardware, and the communications process by allowing operator communication with GENISAS library function calls. These function calls free the programmer from the necessity of

understanding the communications interactions at the system level on diverse platforms.

Figure 4-5. The Puma 762 Robot is shown grasping a waste object from a drum and placing the object in a tray for characterization.

At the same time, the programmer has a versatile and modular "tool kit," useful in the development of multiple systems. All data are passed between processes in ASCII format to avoid any difference in the format of binary data on dissimilar platforms (for example, 16 bit integers vs. 32 bit integers). Integration of the commands and libraries with the Robline server package is complex as the data package is large. Integration involved writing approximately 400 lines of "C" source code. All software is successfully integrated and compiled into the package.

A graphical user interface (GUI) allows operator access to all functions of the singulation process (such as open/close gripper, scan object, calculate grasp, read Jr3) in teleoperational mode. This interface includes data readouts and action selections for the operator. All software conforms to the X-Windows and Motif presentation standards. The GUI was thoroughly tested with the supervisory software in a simulation mode prior to hardware integration.

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Periodically, the operator is required to intervene in situations where the autonomous mode is not sufficient to accomplish the task, or an error has occurred. This feature is known as error handling. Software allows the operator to make necessary corrections and return control of the hardware equipment to the autonomous programs. The GUI software monitors the state of the task operations, including all mechanisms and sensors, at both component levels and system levels. The process control software maintains an in-depth state because of the requirement that transitions between the autonomous and teleoperational modes must be transparent to the operator.

To perform autonomous grasping of waste stream objects, a grasp planner software package was developed and implemented at LLNL in FY92, using a camera-based binocular vision system. The autonomous grasping technology was demonstrated successfully, using this system for the grasping of objects. For the MWO Demonstration, this software package was planned to be used with a structured lighting system providing the 3-D range image data. The structured lighting system was initially

provided by ORNL to LLNL in a prototype/ laboratory form for algorithm integration. For the MWO Demonstration, a more ruggedized and portable system was required to accomplish singulation from both a large collective pile and from a waste drum. Figure 4-6 depicts the structured lighting system.

Figure 4-6. Pictorial representation of the triangulation algorithm for a structured lighting system.

For autonomous grasping, the structured lighting system with 3-D range image data was planned to provide the object's position and orientation. Potential grasp locations were generated by analyzing shapes of a two-dimensional (2-D) projection of the object. Then, in simulation, several possible grasp positions and locations were ranked with a fuzzy logic algorithm. Ranking of grasps combined estimates of the distance from the center of mass of the object; degree of parallel of surfaces to be grasped; smoothness of surfaces to be grasped; distance across the object versus optimum gripper width; and distance to collision with other objects. Results of this analysis generated information such as position, height, width, and orientation for executing the grasp task. Figure 4-7 shows possible parallel grasp orientations using the fuzzy logic ranking algorithm.

Figure 4-7. Possible parallel grasp orientations using the fuzzy logic ranking algorithm.

Experimental results were highly accurate in range estimation. Total cpu time required for generating the grasping information was approximately 20 seconds. Computational time was proportional to the number of objects to be analyzed and manipulated. This technology development integrates structured lighting system calibration, stereo registration, shape analysis, and grasp planning. Algorithms used for the SCOPE calibration followed existing methods (DePiero *et al.*, 1992). Stereo registration was highly parallelized. The

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shape analysis used a fast rate scan algorithm and a euclidean distance map generated from the range image data. Grasp planning used a decision tree, matching dynamic range of grippers to size of the objects (Dougan *et al.*, 1993).

4.2.4 Future Developments

Currently, waste singulation is successfully performed in both a teleoperational mode and an autonomous mode, but to establish a more robust waste singulation system, several areas of development will continue. Ongoing testing and development will continue for optimal performance of the mechanical subsystems, the grasping algorithms, and the 3-D image data acquisition process.

A more flexible robotic gripper system with greater range of motion is a desirable improvement to the singulation system. Greater range of motion for the grippers will provide greater flexibility for manipulation of differing sizes of objects. The new gripper designs might incorporate a V-block type to allow solid grasping of round objects. Gripper designs will incorporate force sensing and force reflection/control capability for higher reliability in grasping. Determination of which gripper is attached to the robot will be incorporated into the robot's controls. This method of determination is necessary if a complete power loss occurs to allow the robot to recognize which gripper is in place after system restart.

Although interfacing software development was completed, appropriate testing of the code prior to the MWO Demonstration was not completed. As time constraints did not allow integration of the singulation process robot controls into the supervisory interface, the singulation process was teleoperationally accomplished using the SNL-developed SMART interface to communicate with the robotic controls. Integration of the SNL-GENISAS communications interface with the Robline simulation/controls software remains an important objective. Extensive testing will be conducted.

A hardware limitation was revealed during the system integration process. When running the SMART software, use of a single ISIO-2 intelligent serial I/O board for communications limited computational capabilities. The addition of a second ISIO-2 serial communications module in the VxWorks VME-bus

system will preclude potential system reliability problems related to communications overload. Improved operator interactions will be achieved by replacing the force-ball input device with a kinematically similar force reflecting master arm for teleoperational manipulations.

Additional software enhancements will facilitate more versatile ease of integration of 3-D sensory data into the autonomous grasping algorithm. The vision sensory system (binocular vision, structured lighting) will be integrated as a Robline device to allow generic device driver interface. This integration will enhance the exchange of different vision sensory systems while changing only one side of the system software. Vision system software will be developed and integrated to make corrections for "view" calculations relative to the robot's coordinate system (end of arm position). Otherwise, a fixed vision system always will examine objects in a pile from only one perspective. The capability will be available to mount the system as an end effector of the robot and to use the robot to place the system in different locations to attempt grasp calculations.

4.2.5 Summary of Accomplishments

The technology development and system integration of the singulation process accomplished all the initial technical objectives. The ability to use a teleoperated robotics system to perform singulation of waste objects was successfully integrated. Waste stream objects were successfully placed, using a combination of teleoperations and autonomous robot programming.

The successful merging of two important software development "tools" for robotics control, (that is, the integration of SNL developed GENISAS software with high level supervisory control via CIMETRIX, Robline software) is a significant accomplishment. All future software developments and system integration efforts will be simplified.

Successful integration of seamless transfer capabilities allowed systems to run smoothly in autonomous mode; transition to teleoperational mode to allow operator intervention; and transition back to autonomous mode once the error condition was corrected or the operator provided higher level decisionmaking. Although the structured lighting system was not reliably integrated for the formal MWO Demonstration, the algorithms

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necessary to calculate a valid grasp from the 3-D structured lighting data were fully developed and tested.

4.3 WASTE CHARACTERIZATION AND SEGREGATION

4.3.1 Introduction

Wastes must be characterized in a mixed waste treatment facility to assure segregation to appropriate processing streams. Waste objects can vary from well-defined and homogenous to poorly defined and heterogeneous. Characterization of both heterogeneous and well-defined homogeneous material is required to confirm records and detect any foreign matter.

For the MWO Demonstration, a rapid, reliable, and efficient method for sorting dry heterogeneous waste was designed, implemented, and tested. The waste was characterized nonintrusively by conveying it through a sensor system that measured the waste's physical properties. A metal detector was used to determine if any significant metals existed in the object and approximate size of the metals. A sodium iodide (NaI) detector was used to measure amounts of radioactive material. Data from force sensors and a profile detector were used to calculate approximate density. X-ray gauge data previously taken at LLNL were applied to determine variations in material density. This information regarding physical characteristics of the waste was installed in an algorithm designed to select the appropriate treatment line for the object.

4.3.2 Objectives

The objective of the characterization system was to integrate a set of sensors so that waste items passing through the system were characterized sufficiently for segregation into different processing streams. As part of the sensor integration, a commercial metal detector was included in the system to determine if any modifications were required for use in a waste treatment facility. Additionally, experiments were performed to determine if metal detection technology could be used for metal discrimination. A representative subset of

DOE's solid heterogeneous mixed waste was chosen for the characterization and segregation process.

4.3.3 Technical Approach

The characterization system was integrated with the singulation and scarifying systems into a waste processing system for the MWO Demonstration. The characterization system operated by receiving waste items from the singulation system; passing items through a set of sensors to qualitatively determine constituents; and conveying items to appropriate waste treatment lines.

Objects Used in the Demonstration. The objects used in the MWO Demonstration were chosen as representative of typical solid wastes in DOE's solid waste streams. Objects were dry heterogeneous solids containing no glass. The largest object was a one-gallon paint can. The simulated waste treatment lines for the MWO Demonstration were the following: radioactively-contaminated wastes; non metal wastes (ceramic and organic); combined metal and non metal wastes; heterogeneous metal wastes; and homogeneous metal wastes. The objects and waste treatment lines are shown in Table 4-1. For the actual MWO Demonstration, four of the treatment lines only received objects and treatment was not performed; for the homogeneous metal processing waste stream, surface cleaning (scarification) of lead objects was demonstrated after receipt of the waste.

The Sensor System and Sensor Integration. Sensors used to determine waste treatment line type were an x-ray gauge, NaI radiation detector, commercial metal detector, JR3 force/torque sensor, and profile detector. Table 4-2 provides information obtained from each of the sensors. Since procuring an x-ray gauge was beyond the scope of this project, x-ray absorption information was obtained by performing computed tomography (CT) scans on each of the waste objects. This information was processed to obtain simulated x-ray gauge data. The processed information was stored in the supervisory control system for retrieval when x-ray gauge data were required.

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Table 4-1. Waste Items Selected in the MWO Demonstration

Object	Treatment Line
Plastic Bottle with Thoriated Lantern Mantle	Radioactively Contaminated
Ceramic Crucible with Thoriated Lantern Mantle	Radioactively Contaminated
Paint Can with Thoriated Lantern Mantle	Radioactively Contaminated
Kimwipes	Non metal (ceramic and organic)
Rubber and plastic gloves	Non metal (ceramic and organic)
Kimwipes in a paper container	Non metal (ceramic and organic)
Small Hammer	Combined metal and non metal
Booties with a Screwdriver	Combined metal and non metal
Pipes of various metals	Heterogeneous metal
Motor	Heterogeneous metal
Lab Jack	Heterogeneous metal
Metal Vessels	Homogeneous metal
Brick	Homogeneous metal
Complex Shape	Homogeneous metal

Table 4-2. Information Provided by the Different Sensors in the Classification System

Sensor	Property
NaI Radiation Detector	Gamma radiation count
Metal Detector Approximate metal volume	Approximate metal conductivity
JR3 Force Torque Sensor	Weight of object
Profile Detector	Approximate volume of material
X-ray Gauge	X-ray absorption of material

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CT scans were performed to evaluate effectiveness of CT as a classification tool. Results of a CT scan of the motor are shown in Figures 4-3 and 4-4. As indicated, CT provides detailed information about the interior of an object. This information can be used to find the proper processing line and to indicate what actions must be taken during processing. While the MWO Demonstration classification system did not use the CT scans, CT is viewed as an important tool in the nondestructive classification of unknown heterogeneous objects.

Analysis of data output from the metal detector demonstrated that the detector could be used to determine the physical properties of the entering metal object. Results demonstrated that the integral of the magnitude of the signal output from the detector corresponded roughly to the volume of the metal in the object. Furthermore, the phase, coupled with the metal geometry, gave an indication of the conductivity of the material. A detailed analysis of the results of the metal discrimination experiments is shown in Appendix A.

Once data were collected, assessment was performed to assure selection of the appropriate treatment line for the object. Properties selected to determine to which treatment line each object should be sent are provided in Table 4-3. Sensor information was assessed by an

algorithm that employed fuzzy logic to help codify results into sets as the sensor information was approximate. This fuzzy logic algorithm provided a descriptor for the specific properties revealed by the sensors. For example, the metal volume of the motor was given the descriptor "large metal volume" since the volume detected by the metal detector was in the large range.

The complete set of descriptors was assessed to find the appropriate waste processing line type. For instance, the motor had the descriptors "large metal volume," "large volume," and "high x-ray absorption variations." These descriptors implied that the object was all metal and that the metal varied in type. The motor was directed to the heterogeneous metal processing line.

In summary, property information was obtained from an object nonintrusively with the sensors described in Table 4-2. Information was sent to a classification algorithm that assigned mnemonics according to fuzzy sets. Properties given by descriptors were analyzed to divert the object to the appropriate treatment line.

Characterization System Layout. The schematic layout of equipment for the MWO Demonstration is shown in Figure 4-8. Activities of the singulation, classification, and scarification systems were integrated within the

Table 4-3. Information Needed by the Different Treatment Lines

Waste Treatment Line	Selected Properties for Determining Treatment Line
Radioactively contaminated	Gamma radiation count
Non-metal	Object volume
Mixed metal/non metal	Metal object volume Object volume
Heterogeneous metal	Metal object volume Object volume X-ray absorption variations
Homogenous metal	Metal object volume Object volume X-ray absorption variations Approximate metal conductivity

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Figure 4-8. Schematic layout of the mechanical equipment for the MWO Demonstration.

limited space set aside for the MWO Demonstration at SRTC. The classification portion of the layout included the tray dispenser, the metal detector conveyor, the process conveyor, and the process side lines.

Objects were moved through the classification system on trays to facilitate detection of object position and to deposit the object in the appropriate location. The tray went from the tray dispenser onto the metal detector conveyor on the side next to the PUMA robot. The PUMA robot grasped an object and then put the object in the tray. The metal detector conveyor moved the tray through the profile detector, the metal detector, and the NaI radiation detector. Readings were taken from sensors as the object passed. X-ray gauge data were recalled from storage and information passed to the classification algorithm to determine waste stream type.

After waste treatment line type was determined, the process conveyor moved the tray to the correct treatment line. If the selected treatment line was radioactive, non-metal, mixed metal/non metal, or heterogeneous metal, the tray was moved to the selected process line for storage. If the appropriate treatment line was determined to be homogenous metal, the tray was moved through the airlock door into the scarifying system where the object in the tray was retrieved for treatment by the IBM gantry robot.

Control System. The classification system was directly controlled by a 68030 microprocessor running in a VME system. The microprocessor controlled the hardware through parallel and serial input and output lines. The microprocessor consisted of driver codes that controlled the functions of each major component or sensor called from another routine or a "server."

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Each "server" was connected through Ethernet to a "client" running on the host machine. The function of the "client" was to channel commands generated by the Robline code running on the host machine to the servers running on the VME system. The host machine ran the Robline code as well as the supervisory control code. The layout of the software is presented in Section 4.5.

Metal Discrimination. The commercial metal detector used in the MWO Demonstration functioned similarly to a transformer. In a commercial metal detector, source coil generates an RF signal that is received by the two coils on either side of the source coil. Receiver coils are balanced so no output results. When a metal object enters one of the receiver coils, the signal out of that coil changes because the metal changes the coupling of the RF signal. The balanced signal measures only change due to entry of the metal.

The metal detector used in the MWO Demonstration was manufactured by Goring-Kerr. The Goring-Kerr detector is typically used to detect metal in food products and can detect ferrous objects under 1 mm in diameter. This unit was chosen because of high sensitivity and availability of a balanced signal through a serial port. The balanced signal was output in the form of magnitude and phase.

Experiments were performed with the metal detector to determine what level of metal discrimination could be achieved. Results and analyses of these experiments are shown in Appendix A. These results demonstrate that phase shift in the balanced signal is related to metal conductivity and weakly related to object size and shape. High conductivity materials such as copper or aluminum were found to have a phase of approximately 80°; medium conductivity materials such as lead, a phase of approximately 70°; low conductivity material such as stainless steel, a phase of approximately 50°.

Enhancements to the current system. Waste characterization and classification was successful for the MWO Demonstration. To enhance the system, a few details will be addressed. Microswitches used to determine the position of the tray caused a misalignment of the tray during transfers, particularly for transfer from the sensor conveyor to the process conveyor. In addition, the activating tong of the microswitches bent with use, making the switches

unreliable. In the future, a non-contact switch will be used.

Another problem resulted from the controller that caused a change in the height of the slider. If the power to the VME control system was cycled while the power to the slider controller was on, an error in the slider controller occurred which required manual cycling of the power to the controller. This caused continual frustration to the operators of the system. This controller must be replaced with a simple stepper motor controller.

Occasionally, another problem occurred in the VME system. The microprocessor failed without warning. This problem is still under investigation.

Finally, because of unanticipated local climatic differences at SRTC, metal rollers in the process conveyor and the process lines began to rust in humid South Carolina. Fortunately, SRTC personnel applied oil that removed the rust and slowed down further oxidation.

4.3.4 Future Developments

For efficient application of a characterization system in a waste processing facility, three areas require additional work:

- Improvements to the CT and x-ray gauge systems
- Enhancements to the classification algorithm
- Improvements to the metal detector.

Information from the x-ray gauge can be improved if the cross section of the scanned object is known. When combined with the x-ray attenuation information, this additional information will indicate if the attenuation coefficient of the material is the same throughout the sample. A non-varying attenuation coefficient will indicate if the object is homogenous. An x-ray gauge system that automatically acquires a cross section of the sample under test and applies it dynamically to the x-ray attenuation data to get an attenuation coefficient, will improve the characterization system.

In the characterization of heterogeneous objects, CT scanning will be a valuable tool. In a waste processing facility, a high speed CT system coupled with an online material identification database will provide the ability

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to identify the constituents of a waste object in "real-time."

A more robust algorithm to handle a higher set of unknown objects and liquids, and a more diverse array of sensors should be developed. While the fuzzy logic algorithm is a major step toward a general classification system, more improvements must be made. Alternative algorithm designs such as expert systems should be investigated.

Results in Appendix A of an in-depth study of the effect of volume, shape, and conductivity on phase can be applied to improve metal discrimination capabilities. This improvement can be coupled with a real time electromagnetic field modeling system for more accurate results.

4.3.5 Summary of Accomplishments

The waste characterization system was installed and tested at LLNL prior to shipment and installation at SRTC for the MWO Demonstration. Upon installation, no major flaws in the layout or controls were found. Except for a few minor problems, the system functioned as designed for waste characterization and segregation activities. A rapid, reliable, and efficient method for sorting dry heterogeneous waste was designed, implemented, and tested. Waste was characterized nonintrusively by conveying it through a sensor system that measured the physical properties of the waste. A metal detector was used to determine if any significant metal existed in the object and the approximate size of the metals. An NaI detector was used to determine if there was a significant amount of radioactive material. Data from force sensors and a profile detector were used to calculate approximate density. X-ray gauge data previously taken at LLNL were applied to determine variations in material density. This information regarding the physical characteristics of the waste was fed into a fuzzy logic algorithm designed to determine the appropriate treatment line for the object. Waste objects were successfully segregated, based on the quantifiable data obtained. An additional study was completed to demonstrate how an industrial metal detector could be used for metal discrimination.

4.4 WASTE PROCESSING — SURFACE DECONTAMINATION

4.4.1 Introduction

The development of a general purpose automated glovebox containment system for processing mixed waste is essential, based on the assessment of anticipated conditions in mixed waste processing facilities, such as, in the processing of transuranic and radioactive wastes. Automated glovebox systems are immediately applicable in the development of automated metal purification technology for metal recycling and reuse. This application will require the development of automated handling and cleaning techniques for metals and for integrated operation of purification equipment. This application and development will lead to recycling and reuse of lead, stainless steel, mild steel, and other alloys. Reduction in the amount of final waste for disposal is anticipated. In particular, process flow diagrams indicate a major lead waste stream of 6,800 kg per week. This equals the processing of 1.5 tons of lead per day in a controlled setting. Therefore, attention to the development of an automated glovebox system for the processing of lead waste is significant currently. Throughout the DOE Complex, the expense of storing contaminated lead will be alleviated by cleaning surface contaminants and recycling lead as radiation shielding or in other contaminated environments.

Automated surface decontamination and cleaning technology for metal recycling and reuse was identified as a significant waste treatment application since these operations are typically labor intensive, tedious, and have a potentially high risk for operators. Lead was chosen as the homogeneous metal to be decontaminated because of historical use across the DOE Complex. Lead often became radiologically contaminated and was a problematic material because, when radioactively contaminated, it is a high profile mixed waste with few disposal options. Surface cleaning and scarifying of lead allows separation of the hazardous and radioactive components from waste streams for easier disposal and possible material reuse.

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4.4.2 Objectives

For the MWO Demonstration, technical task objectives were focused on the application of automated handling and decontamination of the surfaces of homogenous metals. Automated inspection and monitoring of the surface cleaning process was included in the task to ensure operational quality. Since lead materials were identified as a key waste stream problem, initial efforts were focused on the design, development, and demonstration of robotics and glovebox processing equipment for automated lead scarifying. For primary development activities, surrogates were used to avoid generation of mixed wastes during technology development.

The primary technical objective for the MWO Demonstration was the development and demonstration of an autonomous and teleoperational surface cleaning and scarifying waste treatment process for feed preparation and/or treatment of radioactively contaminated metals. This required automated cleaning of easily characterized geometries (bricks) as the primary objective, along with teleoperated cleaning of complex shapes (bent lead sheeting) as a secondary objective.

To maximize automated handling of easily characterized objects, waste item characterization and autonomous grasping were central to success of this task. ORNL was responsible for the development of a mobile structured lighting modeling system that provided waste characterization data of the objects. Using the waste object 3-D sensory data, LLNL was responsible for the autonomous grasping algorithm development and for system integration. An alternative approach to the remote handling of waste objects was teleoperational manipulation.

In support of the primary technical objective, an advanced supervisory control system was developed and incorporated. This advanced system included both a commercially-based, open architecture controller and software algorithms that included remote and sensor-based operation of the glovebox robotics system in both teleoperational and an autonomous mode.

4.4.3 Technical Approach

To demonstrate the feasibility of integrating robotics technologies for surface cleaning of homogenous

metals, a waste cleaning processing system was developed. The target homogenous metal was contaminated lead. The MWO Demonstration sample system used aluminum as a surrogate for lead and paint as a surrogate for radioactive contaminants. Surrogates were used to avoid generation of mixed waste during the technical demonstration.

Processing steps for the MWO Demonstration follow:

- Delivery of tray with homogenous metal waste stream object by conveyor system, into the waste treatment glovebox
- Grasping of metal object with the glovebox robot and removal to the surface decontamination enclosure
- Removal of waste object after cleaning to warm inspection station
- Transportation of object to cold inspection station after determination of an acceptable level
- Placement of object on the pallet conveyor for transport out of glovebox for future use (for example, reuse or recycling of the materials).

Glovebox Telerobotic System. A telerobotic system was included in the MWO Demonstration for the following reasons:

- Separation of the operator from both radioactively and chemically hazardous handling tasks
- Provision of improved efficiency and accuracy with appropriate incorporation of autonomous functions
- Reduction of secondary waste generation associated with operator gloveport operations by limiting gloveport activities to maintenance of the robot.

The telerobot for this system was an IBM gantry with a CIMETRIX controller. The IBM gantry is a six degree of freedom Cartesian robot with a powered electric gripper. The gantry is capable of lifting 50 pounds vertically and has a speed of approximately 3 inches per second. Modular in design, the gantry allows

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maintenance and repairs of all system components remotely, through gloveports.

The operator input device interface for the teleoperational system was a CIS Dimension Six force ball. The force ball measured operator inputs as forces and torques on a ball. These forces were converted to velocity commands to each of the six axes of the robot. A hard push caused a fast movement and a soft push generated a slow movement. With this force input, the operator effectively pushed the force ball in the direction of desired robot movement and the robot responded accordingly.

Telerobotic functions were augmented with membrane key operations of the Dimension six force ball. These function keys included opening and closing the gripper; changing the speed of the robot; operating the upper arm while locking the wrist gimbal in place; operation of the wrist alone; and moving only one joint at a time. By combining these function keys with the force ball, varied operational behavior became available.

In addition to the force ball teleoperation interface, an X-Window menu system interface was developed and demonstrated. The X-Window base interface provided an environment to modify autonomous tasks and to make precision movements. The X-Window interface allowed for control of additional systems including a pallet mover; a down draft table blower; and the scarify tool. These devices were controlled teleoperationally with button operations on the console display.

To implement complete telepresence operations, four cameras were included in the gantry robot work space at manipulation areas anticipated to be close tolerance areas. Cameras were aligned with the robot's horizontal axes to simplify operator commands. This alignment correlated horizontal motion on each video screen with a robot joint.

Scarify Mechanism. A commercially available frozen CO₂ pellet abrasive cleaning system was integrated for surface decontamination of homogeneous metal objects. Several options for the cleaning process were available, but strong industrial support from ALPHEUS and the absence of waste byproduct dictated the choice of CO₂ abrasive cleaning (Figure 4-9). In the chosen system, CO₂ pellets of approximately 4 cubic millimeters are inserted and accelerated with compressed air (Figure 4-10). The impact of the CO₂ pellet against the metal

drives solid CO₂ under contaminating surfaces and spills contaminated material (Figure 4-11). As contaminated material is removed, the CO₂ pellet sublimates and allows the contaminated material to be pulled through a down draft exhaust system. For the MWO Demonstration, the CO₂ was vented into the air. In an actual facility, the CO₂ would be passed through a high energy particulate air (HEPA) filter to separate contaminants from evaporated CO₂.

After initial experimentation with teleoperational cleaning, the teleoperation was revealed to be cumbersome for continual use. Consequently, automation was developed to perform repetitive tasks. The interface for the CO₂ scarifier control was changed to a relay, replacing a manual switch. However, because of the computer controlled CO₂ scarifier, an emergency shutoff was included for safety.

With the CO₂ pellet flow under computer control and with appropriate safety systems in place, the automation of the scarifying system was implemented. The CO₂ delivery tube operated at the freezing point of CO₂ (-78°C). This phenomena had two effects during initial operation of the system. First, in the initial blast the CO₂ pellets were melted and ineffective at cleaning. This effect was quickly remedied by allowing a 40 second initial spray before cleaning began. Second, the CO₂ delivery tube was susceptible to fatigue because of the cold-induced stiffness of rubber parts. To avoid the development cost of a bendable CO₂ delivery system, the scarifier was held at a fixed location, and metal objects were manipulated in front of it.

Because of the anticipated large number of regularly shaped objects (bricks), a completely autonomous cleaning sequence was programmed. This autonomous cleaning system allowed for operator intervention and telerobotic override control either at operator discretion or if an upset condition occurred. The system provided the normal sequence of autonomous grasping, surface decontamination, and automated inspection.

Automated Grasp Planning. The first autonomous grasping step applied the ORNL range scanner (SCOPE). The scope system used structured light sources to develop a range image of the metal object in the tray. Then, in simulation, several possible grasp positions and locations were ranked with a fuzzy logic algorithm. The ranking of grasps combined estimates of distance from the center of mass of the object;

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Figure 4-9. The CO₂ Abrasive Cleaning System uses the ALPHEUS Pellet Cleaner.

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Figure 4-10. CO₂ Pellets of approximately 4 cubic millimeters are inserted and accelerated with compressed air.

Figure 4-11. The impact of the CO₂ pellet against the metal drives solid CO₂ under contaminating surfaces and spills contaminated material.

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parallelness of the surfaces to be grasped; smoothness of surfaces to be grasped; distance across the object versus the optimum gripper width; and distance to collision with other objects. For the MWO Demonstration, the grasping of objects was performed with telerobotic manipulations. Because of delays in obtaining the structured lighting system, the autonomous grasp planning was not completed during the MWO Demonstration. Autonomous grasp planning was later demonstrated at LLNL using a Puma 562 and the ORNL range sensor. The algorithm for grasp planning was developed by ER&WM using Lisp and was structurally the same as the 1992 grasp planning demonstration.

Automated Scarifying. After the object was grasped in the robot gripper, it was passed into the CO₂ surface decontamination system. After the accessible surfaces were cleaned, an object was placed on a stand for a change of grasp position. Before each new grasp was performed, the fingers were cleaned with CO₂ to limit the possibility of recontamination of cleaned surfaces. A second pass completed the cleaning of the object.

After surface decontamination was completed, each surface of the homogenous metal was inspected in a radiological warm cell. Inspections were performed with autonomous robotic manipulations after the metal shape was determined. For the formal MWO Demonstration, only the surface inspections of a 7 x 3 x 1 inch brick were developed. A more complete inspection system will include programming for more diverse and complex-shaped objects.

Each surface inspection task was reduced to four parts. The first stage of inspection was conducted in the radiological warm cell, with an alpha sensor inspection of each surface. During this operation, the object was set down and establishment of a new grasp was established to complete inspection of the brick under the initial robotic gripper position. Since no radioactive material was actually used, the MWO Demonstration dealt only with the robotic material handling aspects.

If below acceptable minimum standards for "clean," the object was passed from the contaminated glovebox area (warm cell) to a clean glovebox (cold cell). If not "clean," the brick was sent back to the scarifying system for re-cleaning. In a real facility, the movement of the robot from warm to cold cell would be accomplished over a down draft table using two robots (one clean

robot in the cold cell, and one contaminated robot in the warm cell). For the MWO Demonstration, resource constraints dictated use of a simplified system. Only one robot was used and the down draft table was simulated.

After the brick was passed to the cold cell, brick cleaning required verification. Two forms of verification were performed. First, a non-contact alpha sensor identical to the warm inspection was used. Second, a contact inspection was conducted. The contact inspection involved moving a swipe along each surface with a constant force. To achieve the constant contact force, a linear constant force spring was used. The spring had a higher speed response than the robot and insured more accurate force control than the robot servo mechanism. The constant force spring had an active range of one inch which required the robot to follow the surface with an accuracy of one half inch. After the swipe was moved along the desired inspection surfaces, swipes were placed in a radiation measuring system. New swipes were placed on the constant force sensor. As no radioactive materials were actually used in this part of the MWO Demonstration, only automated material handling manipulations were conducted. The surrogate contaminate was paint, so a visual inspection was completed by the operator, using a color camera, to determine if the metal objects were "clean." If the cleaning process failed either inspection, the brick would be packed into the warm cell for re-cleaning and the cold cell would be decontaminated.

After metal objects were determined to be clean, the objects were stacked on a pallet for removal to a storage station. The stacking of objects was dependent on the object's shape.

Major Technical Accomplishments. An important aspect of the MWO Demonstration involved use of the robot controller called Robline 3.0.4 from CIMERIX. In addition to the Robline control functions, a state manager and operator interface were developed by LLNL and called the supervisory controller. The supervisory control system and Robline were integrated to provide a platform for off-line programming and true multi-threaded operations. Hardware logistics made this project difficult. Robots and systems to be coordinated during the MWO Demonstration were located at four different national laboratories until a month before the Demonstration. Logistics problems were circumvented by a process referred to as off-line

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programming. Off-line programming is a process of simulated robots and workcells in a virtual environment. As tasks were developed, the planning was tested against the simulation for completeness and accuracy. The off-line programming environment provided a platform to develop region-based collision avoidance and enabled the generation of task programming in simulation, prior to the arrival and integration of hardware.

The simulation environment provided support for regular operations in collision avoidance and data transfer organization. For collision avoidance, all robotic movements were tested in simulation before being executed by the actual robot. For the initial stages of development, a simplified version of collision avoidance was used. The system glovebox was divided into four regions so that a linear motion from any point the robot could reach to the center of the region did not result in a collision. A trajectory plan was developed to move from a region center to another region center. Collision avoidance was simplified to a movement to the center of each region before executing movements between regions. This form of collision avoidance was successful when returning to autonomous mode from teleoperational mode. The controller moved to the center of the region it was in after leaving teleoperations and then moved to the appropriate region for autonomous operations.

Imbedded in the off-line programming were three important features of Robline. First, the simulation programs were the same programs which controlled the actual robot. This eliminated the necessity for the generation of two programs, one for simulation and one for control of the robot.

The second feature of Robline was the simplified parsing requirements. Rather than sending all of the native controller commands and branch statements which often led to difficult programming tasks, Robline used a minimal set of controller commands and executed the branching and condition statements in the simulation package. This feature significantly improved the ability to interface the controller rapidly.

The third feature of Robline was complete multi-threading. This was the least obvious and the most important feature. Multi-threading allows for independent operation of multiple tasks on the same processor. The processor works on each active task for

limited time periods. Aside from allowing multiple tasks to be accomplished simultaneously, multi-threading is a standardized structure for multi-processing to allow running of different programming tasks on different machines.

4.4.4 Future Developments

To establish a more portable grasp planning algorithm, the algorithm will be ported to "C" in combination with Robline utilities in 1994. To facilitate the development of a "C" version of grasp planning, a generalized environment for object shape input will be developed. The system will be a generalized 3-D surface modeling system. Parts of the surface model will be sensed using a mobile range sensor manipulated with the robot. These parts will be combined in the Robline environment for use with off-line programming and graphical simulations.

To improve the ability to grasp complex-shaped objects, an improved tool box of grippers will be developed. Currently, LLNL is using four parallel jaw grippers with one-inch closing movement for each. For objects loosely packed in plastic bags, the closing distance must be increased. These loosely packed objects are either hit by the gripper as it approaches the object, or the gripper can not close sufficiently to contact the object inside the bag. By expanding the gripper closing distance and providing more options, more stable grasp can be assured.

In addition to the expanded gripper tool box, a system to allow the gripper to be used in combination will be developed. For example, to pick up a piece of pipe, two grippers near each end provide a more stable grasp than one gripper in the center. An adaptive fixture to hold grippers and allow work in concert, will greatly expand the ability to pick up complex-shaped objects. In addition to grasp planning in the Robline environment, a surface tracing system will be developed. A surface tracing system will allow for generalized surface inspection and for arbitrarily shaped objects. By maintaining the Robline environment, the portability of the code will be maintained. Additional work will improve user interfaces of the various systems.

A significant user interface development will involve the teach pendant and mobile telerobotic interface design. Since all of the Robline user interface functions

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and LLNL supervisory controller interface Window are Motif X-Window functions, a mobile X-Window will become the teach pendant and mobile telerobotic interface. Occasionally, an operator may wish to make robot manipulations for precision tasks while near the robot. To address these cases while minimizing development efforts, the console control windows will be designed to allow for operations on a mobile X-terminal. In combination with the X-terminal, the force ball and emergency stop button will be combined. As technology develops, wireless Ethernet will be included to improve operation convenience.

4.4.5 Summary of Accomplishments

The scarify technology was demonstrated using CO₂ pellets as the cleaning medium for homogenous metals.

The teleoperational and autonomous grasping of objects, scarifying of metal objects, and inspection of cleaned objects were all demonstrated. Progress on inspection of complex shapes, collision avoidance, and more complicated grasp planning is underway for 1994.

Region-based collision avoidance was used transparently throughout the LLNL portion of the MWO Demonstration. Movements of the robot from region to region were made without collision, independent of position after teleoperations.

4.5 SUPERVISORY CONTROL SYSTEM

The supervisory control system (SCS) includes a high level supervisory control system, a local control system for each technology area, and a menu-management system. The local control system addresses individual processes. The supervisory system and the menu-management system support the individual processes.

4.5.1 Objectives

The MWO Demonstration processes were required to be operated as an integrated package, combining individual automation and robotic technologies into a single, coordinated package of technical capabilities. For the MWO Demonstration, the goal was to operate the waste singulation process, the waste characterization and classification process, and the waste treatment process both in an autonomous mode and in a teleoperational mode with seamless transfer

between modes. Each integrated process (singulation, classification, and scarification) was targeted for simultaneous performance with minimal operational codependency. The SCS was designed and developed to address these design requirements.

4.5.2 Technical Approach

The control architecture for the MWO Demonstration was designed as a multi-threaded control system. Figure 4-12 depicts the MWO Demonstration overall control architecture. The SCS for the MWO Demonstration operated as a multi-level hierarchical structure, interfaced to the graphical robotic simulation package Robline by Cimetric, complementing the off-line programming environment. This environment supported staged simulation development, allowing the designer to configure the complete process prior to the existence of the hardware. The simulated development environment was continued after the hardware was incorporated and served to confirm the accuracy of activities prior to actual equipment operation. Robline supported pre-emptive operations. The Robline package provided a multi-threaded capability, which directed simultaneous commands to multiple hardware controllers. For the MWO Demonstration, this capability was used in the overall design to facilitate multi-processing of technology areas by the SCS.

The LLNL SCS is designed to distribute control responsibilities for the integrated processes across the system, maintaining a high level coordinator and controller to globally track the status of integrated processes. The high level supervisory controller acts as the dispatcher of information as needed for individual technology process areas. The SCS dispatches teleoperational requests made by the operator to appropriate technology process areas. Each of the technology area tasks of the integrated processes have respective local controllers serving as the distributed arms of the SCS. Communications are assigned to the supervisory controller to satisfy notification needs for coordinating conditions and actions. The SCS links Robline with the technology process systems through API and library calls. All interface to the SCS is through menu structures, using the X-Window environment. Menu structures are provided by distributing the display controls to the menu manager arm of the SCS. The distributed design addresses the simultaneous processing objective. Each of the

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technology areas as well as the SCS's supporting tasks are implemented as independently executing processes. This approach of implementing all arms of the SCS as independent processes is consistent with the overall objective of distributing the processing. Figure 4-13 describes the hierarchical design of the SCS and depicts lines of communication between the independent technology and support processes.

The integration of the five identified processes (singulation, classification, scarification, control supervisor and menu manager) requires the orchestration of the communication system. Communications across the technology process areas and the supporting tasks are either requests for actions or requests for data information exchanges.

The design of each independent process of the SCS incorporates an event-driven finite state machine. The finite state machine paradigm facilitates management of asynchronous interactions by dividing a complex system into smaller independent tasks. The multiple communications and directives between the processes are streamlined into single event queues for each task. Events use an object-oriented design, and are available throughout the system. Each event has a uniquely defined value, establishing the communication definition between the sending process and the target process. Upon receipt, the target process performs the task requested or stores the data provided. Sending and receiving of events or data was performed through easily identified macro expansions to achieve concise and recognizable coding. The SEND_EVENT() and SEND_DATA() macros perform the requests and data exchanges. The GET_EVENT() macro expands to acquire both requests and data exchanges. Events use the System V message handling queue facility for delivery to target processes.

State machines are used to define a multi-stepped task, where the state is a single step. Events signal completion of that step and the state then "transitions" to the next step. The state machine paradigm is applied in the SCS because of its usefulness in applications incorporating robots. The innate bi-modal operation of robots (teleoperational and autonomous modes) and the need to maintain information between the modes requires a paradigm which fosters smooth transition, such as the state machine paradigm.

Bi-modal operations of robotic applications require further explanation. The technology areas of the integrated processes, identified as singulation, classification, and scarification, incorporate automation and robotics in varying levels of complexity. The performance of the technology process areas is designed to operate in concert, without human intervention; that is, in autonomous mode. If error conditions occur, the autonomous mode of operation is interrupted. The autonomous mode addresses those operations identified as repetitive, well-defined, and error-free.

Recovery capabilities involving operator interventions are designed into the system. The recovery state is referred to as the teleoperational mode, allowing the remote operation of the automation and robotic systems. The teleoperational mode addresses unusual operations and recovery activities. Teleoperated actions are performed to correct the error or until the autonomous cycle can be reentered.

The design of state machines requires identification of the operational mode. Events are delivered to the process state machine and dealt with based on the operational "mode state." Error and recovery technology directives or small subsets of events cause a state transition to occur. Figure 4-14 demonstrates the generic design of the state machine. The application process generates events with a sending target. The sequential nature of the autonomous mode is maintained by sending the self-generated event in the task-sequence to itself. The transition to the tele-state incorporates a non-sequential approach to the control flow.

The support processes (control supervisor and menu manager) require fewer state transitions because of the lack of automation and robotics tasks. These support processes conform to the "Idle" and "Stopping" design used for the SCS in the MWO Demonstration. An "Active" state replaces the Auto_state and Tele_state found in the technology area processes.

The Graphical User Interface (GUI) of the SCS is a menu-based system which operates under the overall distributed SCS design. It operates as an independent process, receiving requests for menu displays and servicing operator inputs through the event paradigm. The high level menu displays the operations and status

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Figure 4-12. The MWO Demonstration Control Architecture used the multi-threaded capabilities of the Robline Package. The Workcell Supervisory Control System (SCS) is a multi-process controller which maximized Robline's multi-threaded design.

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Figure 4-13. Supervisory Control System hierarchy showing the three technical tasks controllers with the two support tasks. Each of the areas operates as an independent process, with communication through the event queues. The technical task activities communicate to the Robline realtime server through API and library calls.

Figure 4-14. State transition graphs for the technology processes of the Supervisory Control System. The transitions in each process state machine are event driven. The state machine paradigm is universal across the Supervisory Control System with Auto_state and Tele_state undeveloped for the supporting tasks.

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for the integrated workcell. This menu provides button access for operator interaction to configure all sensors and effectors and to impose teleoperational modes on the three technology process areas of the integrated workcell. Each technology area is represented by an individual teleoperational menu, providing a single event access capability and an autonomous mode re-entry capability. Low level error display messaging capabilities notify the operator of off-normal conditions, allowing adjustment to the data entry for error recovery or operator decisionmaking. The menu display facility complements the Robline graphics displays by using the X-Window facility to direct the menus to a separate display terminal. This process enhanced the operator's performance during the actual MWO Demonstration and provided maximum pictorial information to aid in execution of the independent technology process areas.

4.5.3 Future Development

The hardware instrumentation is designed to report error conditions to the SCS with software notifications. Hardware error conditions occurred during the system integration for the MWO Demonstration which resulted in no software responses. The SCS will be expanded to poll devices independently to assure continuous operations. The system will incorporate the ability to interrogate technology area workcells to verify and validate status. A more extensive monitoring capability will be incorporated at the high level to support more complete recovery capabilities.

Currently, the event delivery system uses the System V Message Handling Facility limiting event deliveries to a single central processing unit (cpu). Robust technological growth of automation and robotics is targeted to a multiple cpu environment, where computer-intensive calculations and processing will be distributed over many platforms. The three

technology process areas will reside on individual computers. Event delivery will grow to accommodate the multiple cpu environment and a generic message delivery system. Using TCP/IP, a standard message protocol between the multiple processes, will accommodate this system. This development will be compatible with the current message delivery system.

4.5.4 Summary of Accomplishments

The SCS, designed and developed for the integrated workcell, contained advanced technologies including the event-driven finite state machine for multiple processes and the independent menu manager process.

Previous research assisted the development of controlling systems with finite state machines. Advancing the traditional finite state machines from a sequentially-driven transition machine to a stochastically-driven transition machine was accomplished. The SCS incorporates "indeterminate" event delivery to multiple processes while maintaining the ability to perform sequentially driven tasks.

The menu management feature of the SCS is a unique, innovative X-Windows application. The menu facility operates as a separate process in a multi-purpose environment and responds to event-driven requests and information. Traditionally, GUI facilities are integrated into the application package, requiring the windows polling facility to direct actions in the application. Based on the LLNL innovative approach, the menu manager as an independent process, allows the applications to be performed more efficiently and more directly with Robline. The menu manager facility of the MWO Demonstration requires a unique X-Window applications loop to poll the X-Window display inputs and the event-driven request.

5.0 REFERENCES

- DePiero, Fred and Reed Kress (1992), *Camera Calibration for "SCOPE" Surface Characterization and Object Pose Equipment*, ORNL, Oak Ridge, Tennessee, September.
- Dougan, A. *et al.* (1993), "Demonstration of Automated Robotic Workcell for Hazardous Waste Characterization," *Robotics and Automation Conference*, IEEE, May.
- Johnson, Robert K. (1993), "Vision-Based Autonomous Grasping of Unknown Piled Objects" *Lawrence Livermore National Laboratory Thrust Area Report*, LLNL, Livermore, CA, November.

Appendix A

Metal Discrimination Analysis

March 1994

APPENDIX A: METAL DISCRIMINATION ANALYSIS

This appendix covers in detail the work performed to determine if a metal detector could be used for metal discrimination and to determine the limits of the metal detector sensitivity. This first section gives an analytical description of the operation of the detector and also covers how those results could be used for measuring sensitivity and metal discrimination. The second section covers experiments performed to test the metal discrimination findings. This appendix ends with a conclusion to this work.

Analysis of a Commercial Metal Detector

To understand the results of the metal detection experiments, the relationship between the metal object under test and the output of the metal detector must be understood. The commercial metal detector used here was constructed by Goring-Kerr and is typically used in the food industry to find small pieces of metal in food. The unit contained a digital signal processing (DSP) chip that controlled the functions of the unit, performed filtering of the measured signal, and output the results to a serial port.

The signal is generated from a source coil at the center of the detector that generates a magnetic field that is picked up by two sense coils spaced at equal distances from the source coil (Figure A-1). This magnetic field creates a voltage V_1 in Sense Coil 1 and the voltage V_2 in Sense Coil 2. The output that is measured by the DSP chip is $V = V_1 - V_2$. If the coils are spaced correctly, the outputs V_1 and V_2 are the same and the output measured by the DSP is zero.

Figure A-1. Coil arrangement for Metal Detector

When an object enters the magnetic field generated by the source coil, eddy currents are induced in the metal in the object, creating a magnetic field in the opposite direction to the applied field. As the object passes through a sense coil (in this case, Sense Coil 1), the magnetic field through that coil changes and its output changes. Since the object does not change the field in Sense Coil 2, the voltage measured by the DSP comes from the reverse magnetic field generated by the metal in the object.

To understand the effect of geometry and conductance on the output signal, a simplified formula for this signal can be derived. The output of Sense Coil 1 when no object is in the coil is given by

$$V_1 = -\frac{d\Phi_1}{dt} \text{ where } \Phi_1 = \int_A B_1 e^{j\omega t} dA_1 \quad (1).$$

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$B_1 e^{j\omega t}$ is the magnetic flux density due to the sinusoidal voltage $V_{in} e^{j\omega t}$ input to the source coil. A_1 is the cross sectional area of the sense coil.

A metal object within the magnetic field at the sense coil will have an individual voltage given by

$$V_m = -\frac{d\Phi_m}{dt} = \int_A \frac{d(B_1 e^{j\omega t})}{dt} dA_m = -j\omega B_1 A_m e^{j\omega t} \quad (2).$$

This assumes the magnetic flux across the metal cross sectional area A_m is constant.

This voltage induces a current that runs on the surface of the metal which is generated according to the following formula :

$$I_m = -B_1 A_m \frac{j\omega}{R + j\omega L} e^{j\omega t} \quad (3).$$

The resistance for good conductors (metals) at radio frequencies is given by the surface resistance multiplied by the length of the object and divided by the width. Given a cylindrical metal object of length h and radius a , the resistance is

$$R = \frac{2\pi a}{\sigma \delta h} (1 + j) \quad (4)$$

where δ is the skin depth which is given by

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} \quad (5).$$

The inductance is that of single turn solenoid of length h which is given by

$$L = \frac{\mu \pi a^2}{h} \quad (6).$$

The current can then be reformulated as

$$I_m = \frac{B_1 A_m \omega e^{j\left(\omega t + \frac{3\pi}{2} - \phi\right)}}{\sqrt{\left(\frac{2\pi a}{\sigma \delta h}\right)^2 + \left(\frac{2\pi a}{\sigma \delta h} + \frac{\omega \mu \pi a^2}{h}\right)^2}} = I_0 e^{j\left(\omega t + \frac{3\pi}{2} - \phi\right)} \quad (7)$$

where

$$\phi = \tan^{-1}\left(1 + \frac{a}{\delta}\right) \quad (8).$$

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This current then forms a magnetic field that generates a voltage in the sense coil. This voltage is given by

$$V_1 = \frac{d\Phi_m}{dt} = \frac{\omega \mu A_1 I_0}{2a} e^{j(\omega t - \phi)} \quad (9).$$

This is the signal that is measured by the DSP chip in the Goring-Kerr metal detector. It is evident that the magnitude of this signal is strongly dependent on the geometry of the object and the applied magnetic field. Using the magnitude of the magnetic field at the sense coil and the area of the coil, it is possible to infer the size of the metal object; and limits to the size an object can be sensed.

The phase of this signal can be reformulated as

$$\phi = \tan^{-1} \left(1 + a \sqrt{\frac{\omega \mu \sigma}{2}} \right) \quad (10)$$

to look at material properties. This indicates that if the frequency (ω) and magnetic permeability (μ) are held constant, the phase will vary between 45 and 90 degrees depending on radius (a) and conductivity (σ). This implies that if the radius were known, the materials conductivity can be deduced.

For the case of ferrous material, the magnetic permeability changes due to the applied magnetic field. In this case, the phase will exhibit large variations as the object moves through the system. These variations can be measured to indicate that some ferrous material existed.

If an object with more than one type of metal enters the detector, the phase shift will then become more complex. If the voltage output for material of type E and type F is

$$V_E = E e^{j(\omega t - \phi_E)} \text{ and } V_F = F e^{j(\omega t - \phi_F)} \quad (11)$$

then the phase from a combination of the two materials is

$$\phi = \tan^{-1} \left(\frac{E \sin \phi_E + F \sin \phi_F}{E \cos \phi_E + F \cos \phi_F} \right) \quad (12).$$

At this point it becomes very difficult to determine material type unless the size of each of the materials are known.

Metal Discrimination Experiments Performed

A small set of experiments were performed before the MWO Demonstration to check the validity of metal discrimination with a commercial metal detector. For these experiments, small samples of different types of metals were run through the metal detector and the results were recorded. Additionally, the objects used in the MWO Demonstration were run through the metal detector and the data recorded.

After the data was recorded and the metal detector was shipped, analysis was performed on the data to determine what information could be extracted from the magnitude and phase measurements and to determine how to use this information to verify the analytical results.

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After analysis, it was found that average phase is best calculated by

$$\phi_{ave} = \frac{\sum_i |V_i| * \phi_i}{\sum_i |V_i|} \quad (13).$$

This eliminates unreliable phase information when the magnitude is small. The variations in the phase are calculated by

$$\text{variation}_{ave} = \frac{\sum_i |V_i| * |\phi_i - \phi_{ave}|}{\sum_i |V_i|} \quad (14)$$

Inspection of the results appeared to indicate that the integral of the magnitude inferred volume of the conductive portion of the object. While no direct relationship was found, metal objects of certain size ranges tended to have values in the same range.

The results of these experiments and the analysis are shown in Table A-1 and Table A-2. Table A-1 contains results for the different metal types. Table A-2 contains results for the objects from the MWO Demonstration.

Table A-1. Metal Detector Experiments on Different Metal Disks

Object	Phase	Predicted Phase	Deviation	Integral of magnitude
Iron Ball	133.0	89.9	1.2	1.64E+04
Steel disk upright	121.5	90.0	9.7	1.90E+05
Steel disk flat	101.6	89.9	29.3	1.04E+05
Al disk flat	82.6	83.3	4.0	1.07E+05
Al disk upright	81.6	87.8	1.4	1.72E+05
Brass disk flat	80.4	81.2	5.5	1.11E+05
Brass disk upright	79.0	86.5	1.7	1.83E+05
Copper disk flat	85.6	85.4	2.5	1.17E+05
Copper disk upright	85.1	88.2	0.8	1.93E+05
Stainless disk flat	51.2	70.1	1.2	7.81E+04
Stainless disk upright	50.4	80.1	0.6	1.19E+05
Lead ball	69.1	80.7	0.8	5.07E+04
Brass and Al disks flat	80.2	-	4.6	2.45E+05
Copper and steel disks flat	97.5	-	22.6	2.52E+05

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Table A-1. Metal Detector Experiments on Different Metal Disks (Continued)

Object	Phase	Predicted Phase	Deviation	Integral of magnitude
Copper and stainless disks flat	70.4	-	4.5	2.07E+05
Tap water with 50 packets salt	9.6	*	1.1	1.52E+05
Tap water with 20 packets salt	10.2	*	2.0	5.96E+04
Tap water	0.0	*	0.0	0.00E+00

* = formula not applicable for non metals
 -- = not modeled

Table A-2 Metal Detector Readings for the MWO Demonstration

Object	Phase	Deviation	Integral of Magnitude
Plastic Bottles	0.0	0.0	0.00E+00
Crucible	0.0	0.0	0.00E+00
Gloves	0.0	0.0	0.00E+00
Paper container	0.0	0.0	0.00E+00
Kimwipes	0.0	0.0	0.00E+00
Aluminum complex shape*	88.4	0.2	1.42E+07
Hammer	40.0	3.0	2.85E+06
Lab Jack*	73.6	5.4	1.77E+07
Small Motor*	85.6	1.2	1.69E+07
Paint can*	83.6	0.8	2.07E+07
Screwdriver in booties	154.5	1.0	1.11E+06
Aluminum brick*	88.5	0.6	1.66E+07
Pipes*	66.3	3.8	1.14E+07
Metal Vessels*	67.2	12.7	2.06E+07

* = saturated metal detector head

The predicted phase in Table A-1 was calculated using Equation 8. As the results show, a difference between predicted and real values results. This is because of the assumptions applied in creating the formulas. Better agreement is reached if Equation 8 is changed to

$$\phi = \tan^{-1} \left(1 + \frac{a}{8\delta} \right) \quad (15).$$

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The predicted values are within 4 degrees of the real values for all the metals except stainless steel. These formulas are not applicable for the lower conductivity materials because of increase in the size of skin depth. This factor probably explains the results for stainless steel.

Conclusions

Using a metal detector for metal discrimination is possible, but demands a tighter formulation of the problem before successful accomplishment. The system can be used to sort metals into good conductors, ferrous, and poor conductors, but requires more information for discrimination. The experiments verified that the formulation was correct, but required modification. Additional experiments must be performed to gather empirical information on the effects of size and shape. Eventually, a set of empirical formulas or a dynamic modeling system can be created to use simple measurements of objects to determine metal conductivity.

A formula to determine the sensitivity of the detector was created. This formula can be used to specify the metal detector, given the desired sensing ability, the maximum metal size, and the minimum aperture size. The goal would be to detect the smallest metal piece without saturating the output signal with the largest metal piece.

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