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Advanced Robotics Handling and Controls Applied to Mixed Waste Characterization, Segregation and Treatment*

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ABSTRACT

At Lawrence Livermore National Laboratory under the Mixed Waste Operations program of the Department of Energy Robotic Technology Development Program (RTDP), a key emphasis is developing a total solution to the problem of characterizing, handling and treating complex and potentially unknown mixed waste objects. LLNL has been successful at looking at the problem from a system perspective and addressing some of the key issues including non-destructive evaluation of the waste stream prior to the materials entering the handling workcell, the level of automated material handling required for effective processing of the waste stream objects (both autonomous and tele-operational), and the required intelligent robotic control to carry out the characterization, segregation, and waste treating processes. These technologies were integrated and demonstrated in a prototypical surface decontamination workcell this past year.

INTRODUCTION

The mixed waste problem in the DOE complex is staggering. Over the next five years mixed waste inventories in the DOE complex will approach1.2 million cubic meters. The incorporation of robotics and automation technology at future waste facilities offers key benefits, including: reduced operator exposure, improved efficiency in waste handling, and reduced risk to the public and the environment. The DOE Office of Technology Development Robotics Technology Development Program (RTDP) utilizes complementary skills from across the DOE Complex to assure that these benefits are realized. The objective of the RTDP Mixed Waste Operations (MWO) program is to develop robotics and automation technology for existing and planned DOE mixed waste facilities that store, characterize, and treat mixed waste, and to transfer this technology to industry. This technology can be applied to hazardous and radioactive wastes as well. At Lawrence Livermore National Laboratory technology for material handling of mixed waste has been developed and integrated into a prototypical system with the cooperation of industrial partners. Key technology areas include: non destructive examination of waste items, waste singulation with automated grasp and path planning, autonomous and teleoperated waste processing for surface decontamination; and integration of multiple tasks with state-of-the art intelligent robotics control.

This paper describes the advanced technology development completed during the past 18 months in intelligent robotics control, advanced material handling and non-intrusive characterization. It also describes how these technologies have been integrated to begin solving the mixed waste handling problem from an integrated approach.

TECHNICAL APPROACH

Over FY93 and FY94 LLNL has developed and demonstrated autonomous and teleoperated waste stream characterization, material handling and surface decontamination of complex shaped waste objects.

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Automated cleaning of easily characterized geometries (bricks) were performed in FY93, along with teleoperated cleaning of complex shapes. For autonomous operations the complexity of the shapes were limited to allow for initial development and feasibility demonstration. In FY94, the emphasis was on improving the intelligent robotics controls for autonomous operations, coupling advanced mechanical grasping techniques with automated grasp planning algorithms, and integrating these technological advancements with a proven industrial waste treatment system. An additional emphasis was placed on reliable and time efficient non-intrusive characterization of the waste stream for initial characterization, segregation, and process inspection. This technology development used surface decontamination as an initial catalyst while keeping other waste treatment and processes (plasma hearth furnace, vitrification) in mind for future extendibility. See **Figure 1** for an overall functional flow diagram.

Intelligent Robotic Controls

In FY 94 a key technical objective was focused on improving the intelligent decision making capabilities of autonomous robotic systems . A key emphasis was placed on developing a 3 dimensional surface model that could be used to generate a 3-D representation. This 3D representation would serve as a common data structure for multiple robotic operations or processes. The LLNL team made major technological accomplishments by using this common data structure in model based collision free workcell path planning, grasp planning of waste objects, and object surface path planning/ surface following. The whole process, from developing the 3D surface model to developing the optimized grasp of an object or generating a surface following path plan made utilization of a

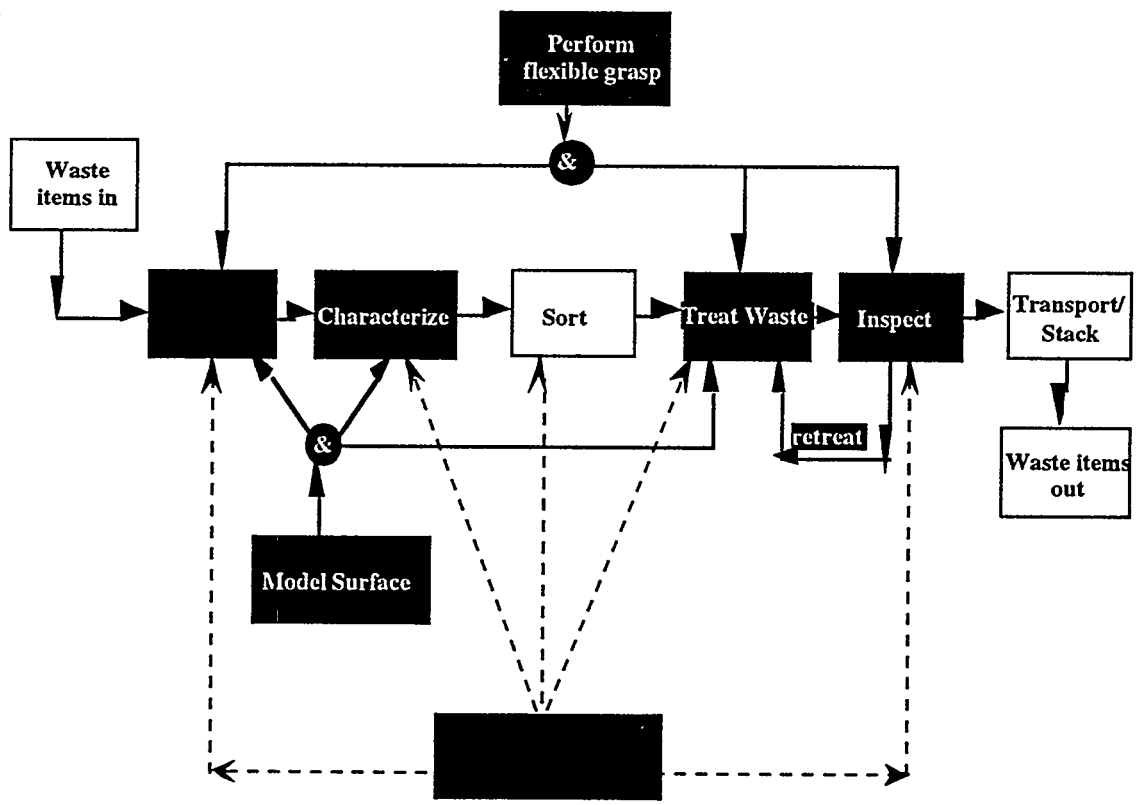

Figure 1: This functional flow diagram articulates the mixed waste processes requiring intelligent robotics controls, flexible grasping, and characterization technologies.

common hardware system and graphical controller. By doing so, information sharing and data transfer between the different intelligent robotics processes was optimized. Figure 2 describes the intelligent robotic controls schematic.

Surface modeling

The objective of the autonomous surface modeling system was to accurately represent full 3-dimensional surface models of unknown objects in the graphical simulation environment. To adequately characterize the robotic workcell and objects within that workcell the range image data was acquired via a stereo vision range sensor system. The range imaging data was then transformed into surface models using a process called polygon representation. The polygon representations were developed based on several steps: mapping the range data to a flat grid, evaluating and charting areas of equal height values, detecting and comparing edges within these areas, representing the areas with polygon corners and finally constructing the 3D polygon representation. Polygon representation provided the common data structure for path planning, grasp planning, and surface following algorithm development and execution.

Path planning

The objective of the path planning process was to provide collision free paths through the robot work space when complex shaped objects were in the robot gripper or when changes occurred in the robotic workcell. Algorithms were developed for a technique known as the "collision free highway" and implemented as the workcell collision avoidance path planner. The "collision free highway" is a path, or highway, within the workcell where it is known to be collision free based on extensive preprocessing.

The "collision free highway" was pre-determined and optimized by moving the simulated robot, with large objects in hand from region to region in the work space. This process was completed for each of the regions in the reachable section of the robotic workcell. All autonomous tasks were designed to end with the robot in the regional collision free space. This allowed for the arbitrary request of autonomous tasks without the worry of potential collisions. Tele-operations of the robot were also performed and then collision free resumption of autonomous tasks were resumed. This method of collision free workcell path planning was designed to

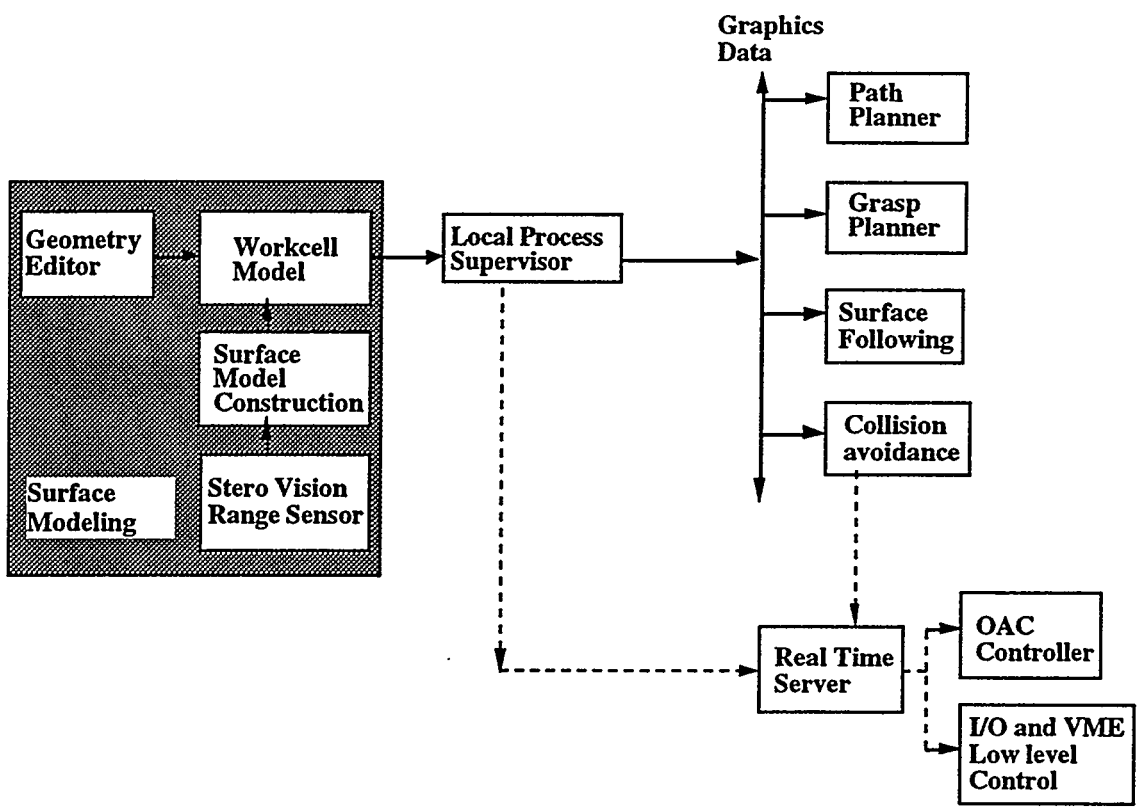

Figure 2: The 3D range image information was integrated with path planning, grasp planning, and surface following algorithms to develop intricate paths or force vectors required to grasp, handle and treat waste objects.

interface with the autonomous workcell modeling system, and to use the common data structures thereby limiting the necessary operator interactions.

Grasp planning

The grasp planner algorithm provided an optimized grasp of an unknown object using the surface model data and the common data structure. This grasping optimization was developed within the graphical simulation environment and then executed by the robot within the workcell. Initially the grasp planner algorithm analyzed the 3D polygon representation of the objects to be grasped and generated several possible locations and orientations for grasping of the object, whether it is an individual object, or one among multiple objects. The algorithm used a list of criteria to rank the possible grasp options. Each attainable grasp was ranked based on these seven criteria. They were potential collision, object clearance, centroid distance, height of grasp standard deviation of surface angle, maximum deviation of clearance and surface contact. Through analysis, a value corresponding to each criteria was obtained. At the end of each grasp analysis, the grasp position was ranked based on a weighted summation of the seven criteria. Adjusting the relative weights of the values obtained from the seven criteria determined the best grasp location. These weights were user-defined and could be changed as desired. The best grasp position corresponded to the position with the highest ranking value. The result of the grasp planning analysis was then used to drive the robot to pick the waste object at the location and orientation in the form of position and angle.

Surface following

The generation of a surface following path is a fundamental requirement for material handling and processing operations such as surface cleaning with a required stand-off distance or inspecting an object with required surface contact. The surface path generation system was greatly simplified by utilizing the 3D common data structure as it's basis. By using the polygon representations of an object simplified the surface following path generation by creating a path that moves along the a single polygon and moves between the defined polygons. The vertices of each polygon were used as the point of interest for the surface following algorithm. In the example of the surface contact inspection task accessing the vertices of each polygon of a scanned object allowed the tool to be moved along each surface in simulation and then a path of the needed movements were recorded. After the surface following path was generated and recorded on the surface of the simulated object, the robotic movements between each polygon were determined using the collision free workcell path planning algorithm.

Advanced material handling

In addition to the intelligent robotic controls a flexible grasping capability was developed to allow grasping and handling of complex and potentially unrecognizable shapes. The prototype gripper design incorporated a lead screw and was designed to meet functions and requirements specific to handling complex and potentially unknown waste objects, either bagged or unbagged. As a first flexible grasping system to be incorporated into the treatment cell the lead screw design was selected for fabrication for it's versatility in handling a diversity of objects.

Advanced gripper tips designs were also integrated on the gantry robot gripper system compatible with tips being used on the lead screw design. This compatibility allowed gripper tip enhancements to be incorporated in all grippers. After multiple gripper designs were evaluated via a bench top object handling system, the selected gripper tip design was based on how many diverse objects could be handled and the manufacturability of the tip designs. The difficulty of modeling the final design by the grasp planning algorithm was taken into account as well as strength and fracture toughness. Finally, the tip design was evaluated on what it offered that a simple flat edged gripper tip did not. The final tip design consisted of flat, rounded faces, and sharp edges integrated into a single design in a 2-1 interlocking configuration .

Non-intrusive characterization

Characterization of mixed wastes (which are both radioactive and otherwise hazardous) requires that all hazardous and non-conforming materials and radioactive sources be identified and localized. Comprehensive and accurate characterization provides information required to determine if a waste item is treatable or has been adequately treated. Much of the required information can be provided without the need to take representative samples to an analytical laboratory. The final waste form must meet federal EPA, state and other applicable regulatory requirements and it must do so in a cost effective manner.

For this project, a treatable waste object was defined as a homogeneous metal object that had external radioactive or heavy metal hazardous contamination. We developed sorting and inspection requirements, and assessed viable non-intrusive techniques to meet these requirements. Radiography, tomography and x-ray fluorescence were the technologies selected. Selected mock waste items were characterized, and minimum detectable amounts of materials were determined. We unambiguously identified hazardous inorganic materials on the surface of objects and we found the presence of heavy metals within objects. We determined volumes (computed tomography) and surface area densities (x-ray fluorescence) to within a few percent. We calculated and confirmed minimum detectable amounts

of materials. These detection limits depend upon everything else that was present, but range down to sub-milligram per square centimeter levels for heavy elements by radiographic and tomographic methods, and below the microgram per square centimeter on the surface by x-ray fluorescence.

Increased efficiency was demonstrated by integrating radiographic with tomographic data. A technique was developed using only the radiographic data where the material is homogeneous (fast), and then switching to tomography in those areas where heterogeneity is detected (slower). A tomographic technique to quantify the volume of each component of a mixed material was also developed. This was useful for determining ash content.

Technology Accomplishments

The integration, testing, and demonstration of the previously described technology subsystems was completed mid September 1994. The sub-systems integrated were the intelligent robotic controls (path planning, surface modeling and following, and workcell calibration), the flexible grasping system, and the industrial surface decontamination system. Multiple dry runs of the integrated system allowed for problem identification and system optimization. Integrated demonstrations began in September 1994 for automated material handling of complex shaped waste objects in waste characterization, handling and treatment processes.

The process of generating a surface model providing a common data structure for the intelligent robotics control processes proved to be highly successful. The generation of the surface model was computational simplified by utilizing structures already existing in the commercially available graphical simulation environment. By using the polygon representation approach to providing the common data structure the surface following process as well as the path planning and grasp planning were simplified in the development phase because of sharing common data and algorithm information between the processes. As an example, this simplification of the surface following process allowed for inclusion of robotic controller capabilities into the path planner and combining the surface path information with other tasks like grasp planning.

This integrated material handling system comprised of the lead screw smart clamping fixture, and the innovative gripper tips were integrated into the automated material handling testbed for grasping and holding of complex shaped objects in the waste treatment workcell. This mechanical flexible grasping capabilities were integrated with the grasp planning algorithm and proved to successfully pick up and handle multiple complex shaped object throughout the treatment and inspection stages of operation. This marriage of hardware and software has led to innovative material handling capabilities.

An in depth document was developed on MOSAIC, an Internet multi-media browser as a documentation medium for the many characterization accomplishments. This document was used to demonstrate the ability to share data and information world-wide. This document will be accessible from other national labs and the outside community for viewing.

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