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ROBUST TELEROBOTICS — AN INTEGRATED SYSTEM FOR WASTE HANDLING, CHARACTERIZATION AND SORTING

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ABSTRACT

The Mixed Waste Management Facility (MWMF) at the Lawrence Livermore National Laboratory (LLNL) was designed to serve as a national testbed to demonstrate integrated technologies for the treatment of low-level organic mixed waste at a pilot-plant scale.[1] Pilot-scale demonstration serves to bridge the gap between mature, bench-scale proven technologies and full-scale treatment facilities by providing the infrastructure needed to evaluate technologies in an integrated, front-end to back-end, facility. Consistent with the intent to focus on technologies that are ready for pilot scale deployment, the front-end handling and feed preparation of incoming waste material has been designed to demonstrate the application of emerging robotic and remotely operated handling systems. The selection of telerobotics for remote handling in MWMF was made based on a number of factors - personnel protection, waste generation, maturity, cost, flexibility and extendibility.

Telerobotics, or shared control of a manipulator by an operator and a computer, provides the flexibility needed to vary the amount of automation or operator intervention according to task complexity. A telerobotic demonstration is needed to prove it's potential to increase productivity of operations. As part of the telerobotics design effort, the technical risk of deploying the technology was reduced through focused developments and demonstrations. The work involved integrating key tools 1) to make a robust telerobotic system that operates at speeds and reliability levels acceptable to waste handling operators and, 2) to demonstrate an efficient operator interface that minimizes the amount of special training and skills needed by the operator.

This paper describes the design and operation of the prototype telerobotic waste handling and sorting system that was developed for MWMF. The work was performed at LLNL in collaboration with Schilling Robotic Systems and with the support of Oak Ridge National Laboratory. Key elements that contributed to robust teleoperation include a truly seamless transfer between teleoperation and autonomous operations, a major advance in whole-arm to whole-workcell collision avoidance that is operational during all autonomous and teleoperated moves, force compliant arm behavior, and a real-time collision-free path-planner. The operator interface demonstrates key elements of the MWMF design including a force-reflecting hand controller that provides operator inputs in a novel hybrid position/rate mode, a speaker-independent natural-language based voice-recognition system, and a reconfigurable graphics and video display system that can be tailored to the operator. The system has been in operation since June, 1996.

I. INTRODUCTION

Mixed waste is a growing national problem. An estimated 190,700 m^3 of low-level mixed waste was in storage at Department of Energy (DOE) sites across the nation in 1993 and another 49,340 m^3 is expected to be generated during the period from 1994-1997.[2] In addition, other industrial sectors, including the medical and academic community also continue to store and generate mixed wastes at many sites across the US. Few acceptable treatment and disposal methods for mixed waste are currently available, resulting in increased storage requirements at DOE and other mixed waste generators' facilities.[3] It is expected that, without development of credible solutions for the disposal of these wastes, authority to store mixed waste under the Federal Facilities Compliance Act of 1992 (FFCA) will be jeopardized.

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The Mixed Waste Management Facility (MWMF) at the Lawrence Livermore National Laboratory (LLNL) was designed to serve as a *national testbed to demonstrate integrated* technologies for the treatment of low-level organic mixed waste at a pilot-plant scale. Pilot-scale demonstration of the technologies serves to bridge the gap between mature, bench-scale proven technologies and full-scale treatment facilities by providing the infrastructure needed to evaluate technologies in an integrated, front-end to back-end, facility. Consistent with the intent to focus on technologies that are ready for pilot scale deployment, the application of emerging robotic and remotely operated handling systems was demonstrated as part of an integrated front-end. The front-end consists of waste receipt, initial screening, characterization and sorting, and preparation as shown in Figure 1.

Since waste received into a typical treatment facility may be very heterogeneous and may not yet be fully characterized, the front-end needs to be both flexible and robust. The degree of uncertainty in characterization also drives the need to be conservative in protecting the operator from unanticipated hazards in the incoming waste material. A remotely operated telerobotic handling system for preliminary characterization and sorting addresses many of the major uncertainties in the front-end, removing the operator from the hazardous environment during the important initial characterization process. Once items have been through sorting and preliminary size reduction, they are much more amenable to more traditional handling systems - conveyors, feeders and storage hoppers. A more complete description of the front-end system design can be found in Reference 4.

The primary use for remote handling in MWMF is at the preliminary sort station where solid containers are dumped into a sorting tray, small particulates are screened out and larger objects are sorted with the assistance of various cameras, sensors, and a real-time radiograph. This initial sorting operation segregates individual items, generally in bags, into waste stream categories that include inorganics (glass, ceramics and adsorbents), metals, cellulosics (paper and wood), and plastics. Items that are determined to be above radiation thresholds are segregated for repackaging at this point as well. Remote handling technology will be used because received waste will not yet be fully characterized; items may be heavy, awkward and/or physically hazardous to handle; and, the container opening, emptying and size reduction operations will likely release hazardous dusts and vapors. The ability of telerobots to perform routine remote operations autonomously gives them potential for improved productivity over a strictly teleoperated remote handling system.

The primary goal of the Feed Preparation design team was to design and deploy a robust front-end system that can be operated by hazardous waste management technicians (not Ph.D. scientists) to meet the initial waste preparation needs while providing a smooth upgrade path to incorporate technology advances as they occur. To meet this goal, the design focused on the following criteria:

- Provide robust teleoperation.
  - Meet human ergonomic speed and dexterity requirements
  - Provide error-free, stable, operation
  - Prevent damaging collisions between the arm and the workcell
- Provide reliable autonomous tool changes and waste disposal actions
- Achieve rapid and smooth transfers between teleoperated and autonomous modes.
- Minimize the amount of training and experience an operator needs to be productive using the system.

The following sections detail how these criteria were met with the design.

II. TELEROBOTICS DESIGN

The telerobotic task is a remotely operated waste characterization and sorting task where the operator performs object grasping and initial item characterization in primarily a direct-view environment, while the autonomous system handles additional characterization and waste disposition. In addition, autonomous modes are used for tool changing, radiation scanning of drum contents on the sort table, and clean-up and decontamination of equipment between process runs.

There are three primary pieces of equipment that are used to perform most of the discrete item and container handling in the feed preparation area — a remotely operated manipulator, a floor mounted linear rail in the preliminary and secondary sorting area, and an overhead gantry with a telescoping mast. There are many other supporting pieces of equipment including the strongback and transporter for drum transfer into and out of the cell; operator gloved access areas for manual operations; a drum dumper; drum staging racks with weigh scales; an x-ray machine to identify hidden items that might damage the shredder; and a weigh/sort tray for items destined for the shredder and final feed preparation. The general equipment arrangement is shown in Figure 2.

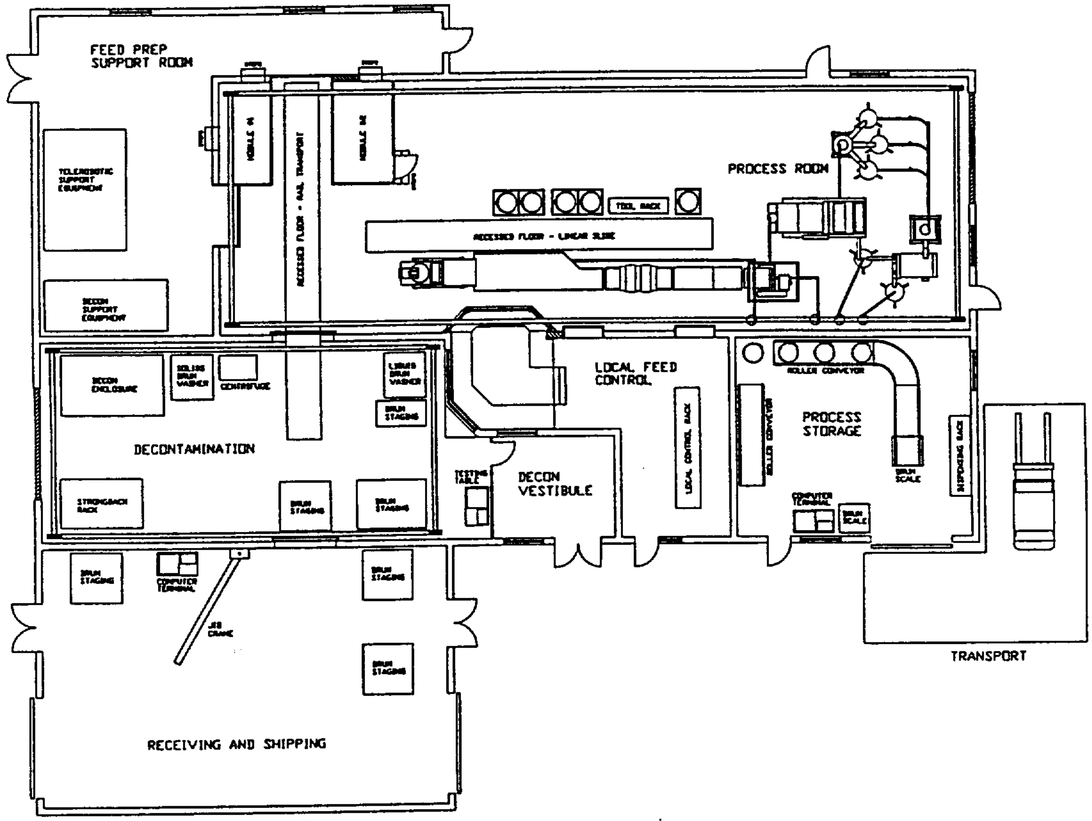

Figure 1. Waste receipt and feed preparation floorplan

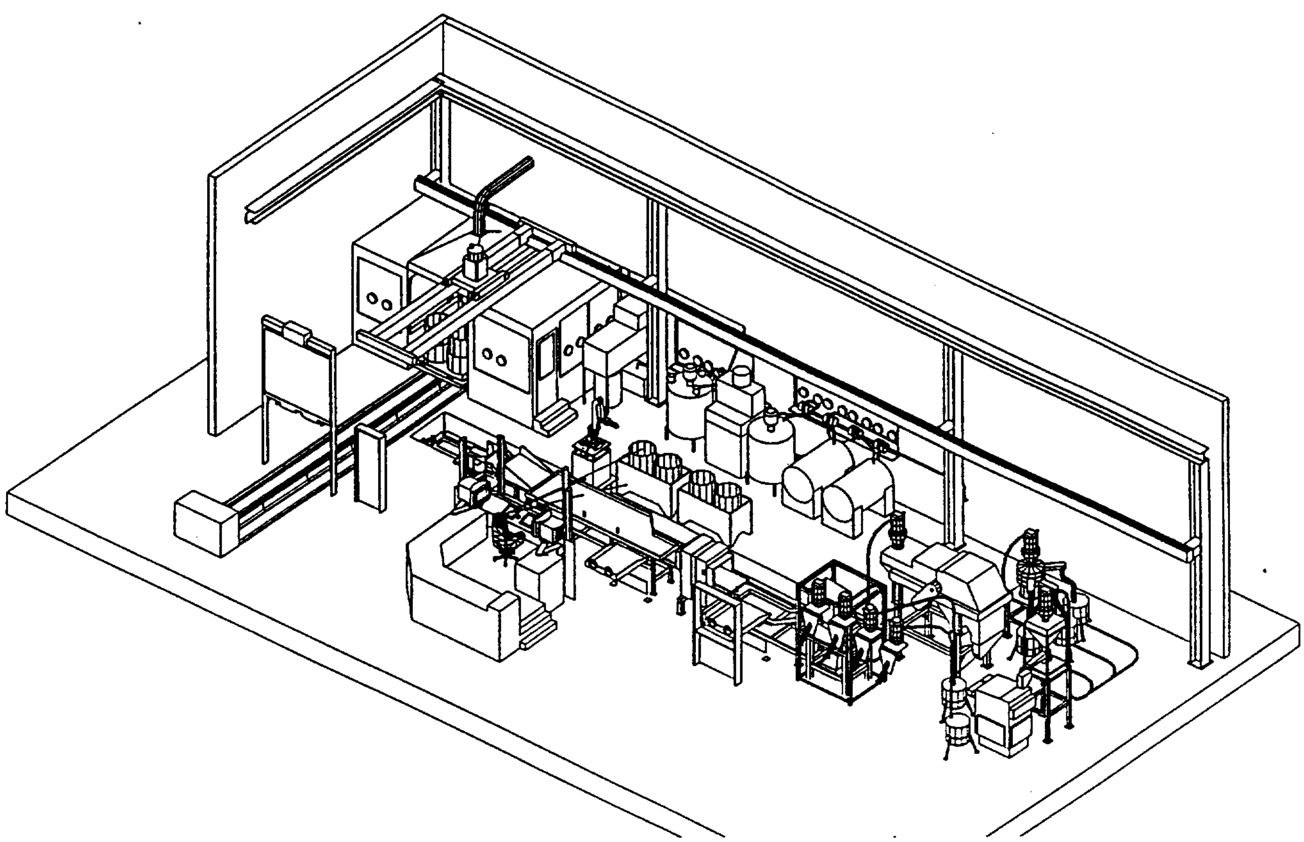

Figure 2. Feed preparation equipment arrangement

During routine operation, the manipulator is mounted on the linear rail to access the preliminary sort tray, characterization equipment, tool racks, and waste stream output drums. Standard interfaces on the manipulator, crane and rail allow the manipulator to be picked up by the crane for non-routine operations, including reaching into containers and areas that cannot be accessed using the rail mounted configuration, or for decontamination and clean-up operations after a spill or material release. The system is operated from an adjacent control room that overlooks the preliminary sort station. Cameras mounted to each side of the control room and directly over the preliminary sort area are used to generate 3-dimensional images of the waste pile, individual grasped items, and the waste level in the sort drums.

As acceptable material exits the sorting process, it is weighed, shredded, and metals are removed using magnetic and paramagnetic separators. The remainder is screened and segregated into various organic and inorganic streams by density separation. Since the processing units chosen for MWMF are small-scale commercially available systems used in the food processing and pharmaceutical industries, they can be readily decontaminated. Material is moved between the enclosed units using pneumatic transfer systems. Finished feed stock is characterized and blended to meet treatment demonstration needs.

III. PROTOTYPE DEVELOPMENT

During the MWMF front-end design effort, the technical risk of deploying the technology in MWMF was reduced through focused developments and demonstrations on a plant prototypic system. Conventional feed prep equipment was evaluated primarily through demonstrations and services provided at vendor sites. The telerobotics development was performed at LLNL with the involvement of Schilling Robotic Systems and Oak Ridge National Laboratory (ORNL). The cell, shown in Figure 3, consisted of a sort table on air springs with 25 mm travel, waste barrels, and a Schilling Titan 3 manipulator with a C30 VME interface. The operator interface consisted of a Cybernet CyberImpact hand controller, Motorola 68060-based VME controller, and Sun workstation with a flat-panel display. The software configuration included Cimetrix' Robline package for graphical simulation and control, RTI's ControlShell package running over Wind River Systems' VxWorks real-time operating system, and Nuance's CORONA speaker-independent voice recognition system.

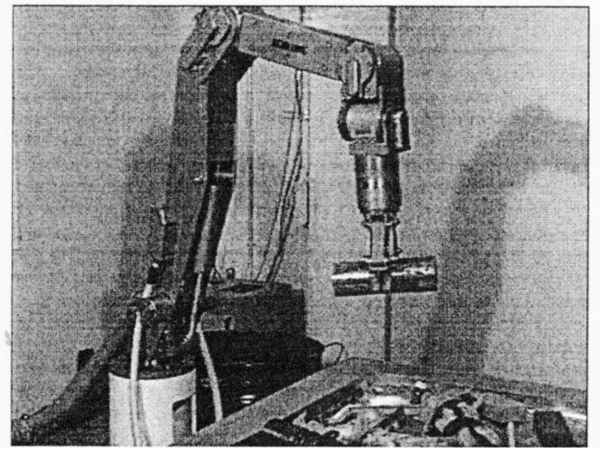

Figure 3. Telerobotics prototyping cell

The engineering development work focused on integrating key tools to 1) make a robust telerobotic system that operates at speeds and reliability levels acceptable to waste handling operators and, 2) to demonstrate an efficient operator interface that minimizes the amount of special training and skills needed by the operator. Robust telerobotics involves three key capabilities — robust teleoperation, reliable autonomous operations, and seamless transfer between teleoperated and autonomous modes. The operator interface elements include a method for effective data collection and presentation for item characterization, an ergonomically efficient hand controller interface for telerobotics, and a telepresence system. Each of the major thrusts will be described below.

A. Robust Teleoperation

The manipulator provides the dexterity, reach and motive force required to handle items at the speed and acceleration needed for teleoperation. A standard interface at the manipulator base, along with mating interfaces on the linear rail and overhead crane, provide the flexibility needed to locate the manipulator in the proper orientation relative to the task space. For dexterous tasks, the manipulator must respond and travel fast enough to avoid delaying the operator. Studies have shown that manipulator must be capable of operating at speeds close to 1 m/sec and the system bandwidth needs to be in the range of 9 to 25 Hz.[5] While dedicated joint-to-joint teleoperators can achieve 1 m/sec tip speeds, robot systems operated as teleoperators had not. Robotic operations require tighter position controls, forward and inverse kinematics, input-output device correspondence, and collision avoidance — a much more demanding computational problem that had not been demonstrated to operate reliably at plant-prototypic speeds. Therefore, the most critical portion of the telerobotic task was to achieve robust teleoperation in a robotic system. This involved developing a stable control loop at a high enough rate to meet teleoperation speeds while incorporating collision avoidance and force compliance.

For platform stability, LLNL chose to follow ORNL's lead and implement the real-time control system in Real Time Innovations modular, component-based, ControlShell package. In fact, ORNL agreed to collaborate with us and provided their dual-arm Titan II control system for adaptation to LLNL needs. This allowed our staff to bring the initial Titan III configuration up in a shared control mode in approximately two weeks, with one third of the modules being from ORNL, one third from the RTI library and the final third generated at LLNL. ControlShell provided the development environment and diagnostic tools needed to incrementally develop and test the control system and achieve a stable system configuration.

The Titan III manipulator has impressive strength and power, able to handle 120 kg loads at up to 1 m/sec. This necessitated special precautions when using the arm around expensive equipment that can be easily damaged. A real-time whole-arm model-based collision-avoidance system was developed that met servo-loop rate requirements. The collision avoidance system detects impending collisions between each robot link and every other link and work cell component at a resolution of one cubic inch. The system provides dynamic joint limit updates at a rate of 40 cycles per second on a 60 MHz Motorola 68060 CPU. This exceeds the vendor-supplied collision checking speed by a factor of around 5000. The collision avoidance system allows surfaces to be identified as no-touch zones, or as limited force zones. In limited force zones, the collision avoidance system slows the arm prior to contact to allow the force compliance system time to react on contact. The collision avoidance system is operational during both teleoperated and autonomous operation modes.

The force compliance system uses a JR^3 wrist force/torque sensor integrated into the arm by Schilling Robotic Systems. The compliance control system limits the force applied to surfaces to a predefined limit, approximately 300N in the downward direction on the sort table, with a 1000N lifting limit. As currently configured, torques are not controlled until they approach the limit of the force-sensor's operating range. At that point, the arm is E-stopped. Operational tests indicate that the final system should be more torsionally compliant to avoid these occasional E-stop trips.

Robust teleoperation including collision avoidance and force compliance was operational in February 1996. After addressing shared control technical issues, a number of additional teleoperation modes were implemented including a variable gain between the mini-master movement and the manipulator range of motion; dominant axis mode — which ignores input commands along all but the largest axis of movement; fixed orientation mode — which fixes the orientation of the gripper in world space but allows translation (good for moving around open liquid containers without spillage); and a hybrid position/rate input mode — which reduces the need to reindex the master.

The achievement of collision avoidance and force compliance in the hybrid input teleoperation mode proved robust teleoperation was possible with current technology.

B. Autonomous Operation

The autonomous tasks include waste disposition, tool changing, waste pile scanning and decontamination of the sort table. Of these, tool changing and decontamination are standard tasks that can be preprogrammed and enhanced using force compliance. The baseline design for preprogrammed tasks is a model-based path storage and retrieval system tied to the real-time trajectory generation system. Path recall is achieved using a voice command or on-screen menu system. Since preprogrammed tasks were well understood, they were not prototyped.

Waste disposition and waste pile scanning require both real-time input on the shape of the object of interest and real-time collision-free path planning. To meet design requirements, only a slight delay is tolerable between the time the robot is dispatched to it's destination and arm movement begins. For the prototype, a delay of two seconds was considered too long to keep an operator waiting. In the actual system, one second would likely be the upper limit. Therefore, the system had to incorporate a 3-dimensional "blob-detector" and a real-time collision-free path planner that could both run within a nominal one second window. For this task, the "blob-detector" terminology was coined because, for collision avoidance, only a low resolution shape was needed — a volume element, or voxel, of 2.5 cm on a side was sufficient.

LLNL's prior work in binocular stereovision for waste item geometric characterization provided higher resolution than necessary and hadn't yet evolved to meet the MWMF speed requirement. Therefore, a simple binocular system was designed that looked at orthogonal views of the object and generated a largest envelope object size at video frame rates using a Datacube MV20 VME system.

This shape was converted into the voxel structure of the collision avoidance tree for path planning.

Real-time collision-free path planning was possible through the use of the high-speed collision detection system. The same ControlShell components running on the real-time controller for collision avoidance were loaded onto the Silicon Graphics workstation to run in concert with the robot simulation and control package. On the SGI, the collision detection update rate is nearly one kilohertz for the same model. At this speed, the path planner can determine an unobstructed route to the destination using a directed maze search algorithm with the collision detection algorithm testing for collisions at each step. The time required to plan a path to the waste drums from the sort table is less than a second — within the window needed to meet operator ergonomic needs.

The ability to quickly assess an object's shape, attach it to the manipulator arm geometry, and plan a path in real-time proved that the "robotic" portion of "telerobotics" was viable for our application. All that remained was a method to efficiently use both modes during task execution.

C. Seamless Transfer

Seamless transfer between teleoperation and robotics is relatively straightforward in the ControlShell environment. ControlShell's event-driven state machine is used to activate different configurations of control system components based on the current state of the machine and sensed events. In the MWMF system, depressing the deadman switch at any time triggers the state machine to enter teleoperation mode. Even during the middle of autonomous moves, the operator merely has to grasp the hand controller, squeezing the deadman switch, to gain full control of the manipulator. This gives the operator the flexibility to interrupt the manipulator's approach to the waste barrel if they are not confident the path will clear an obstacle, or to intercept the arm's return to the sort table to rearrange items in the barrel if desired. Entering autonomous mode is accomplished by voice command.

D. Operator Interface

The operator interface provides two primary functions — control of the telerobotic sorting system and collection and display of waste characterization information. In addition, displays at the operator station allow the operator to remotely control and monitor the conventional process equipment and interact with the supervisory data acquisition and control system that is used for work scheduling, material accountability, and reporting.

After looking at more conventional operator interface approaches, LLNL chose to implement a console-less system that uses a speaker-independent natural language-based voice-recognition system and a chair-mounted force-reflecting hand controller for operator input, with a reconfigurable graphics, audio and video display system for output. The hand-controller is designed to be mounted to either side of the operator chair for left- or right-handed operators and the displays can be moved around the viewing area as needed.

One of the key goals of the operator interface design was to facilitate the use of a variety of different input and output devices based on operator preference and technology availability. The range of game controllers and virtual reality interfaces that are currently being developed provide a rich set of possible future interface tools. Therefore, we chose to focus on designing a system that allows an operator to select the interface tools they want from the set of those supported. Currently we have developed input interfaces for a force-ball, an RSI inverted stewart-platform non-force-reflecting 6-DOF master, and a Cybernet CyberImpact force-reflecting 6-DOF master. A fully configured control interface for a single manipulator system might consist of a 6-DOF master for one hand; a menu select system and E-stop for the other hand; a voice recognition system; a monitor for displaying the computer graphic world model and 2D video; a 2D text display for menus and confirmation messages; and a 3D stereovision display.

The graphics model display is a key element since it allows the operator to select which of the cameras or views represented in the model is the controlling operator view. This allows the transformation matrix representing that viewpoint to be used to correct the input/output relationship between the operator's command and the manipulator arm (e.g. When an operator selects a view and wants to move the manipulator to the left in that view, they can move the control arm to the left and the manipulator will move to the left.). Since our remote operations are primarily direct-view, the 3D stereovision and 2D graphics displays are designed to pivot out of the way during most operations, leaving the menu/text display, voice input and hand controllers as the primary interface tools. This being the case, we chose to prototype this portion of the system to validate it's ease of use and utility.

There are a large number of hand and master arm controllers on the market and their capabilities vary widely. They can be classified as passive or active. Passive controllers accept operator input as position or force commands but have no capability to reflect position or force of the manipulator back to the operator. Active, force-reflecting hand controllers, are actively driven to provide operator force feedback cues on the state of the manipulator arm. In addition, through the use of virtual forces, the robot force information can be augmented with additional information representing impending collisions to cue the operator to stay away from a particular area. Hand controllers are typically end-point control devices while master arms are usually full size kinematically similar manipulator arms akin to traditional master arms in master-slave manipulators. LLNL performed surveys of the industry, acquired and evaluated a number of active and passive systems, and reviewed a number of studies on other hand controller performance evaluations.[6,7] Since most dexterous tasks (grasping, fine manipulation, etc.) take place in relatively small volumes (.75m x .75m x 1m), the Cybernet force-reflecting hand controller shown in Figure 4 was selected for initial deployment in MWMF.[8] Cost and space were also major drivers in the selection of a mini-master.

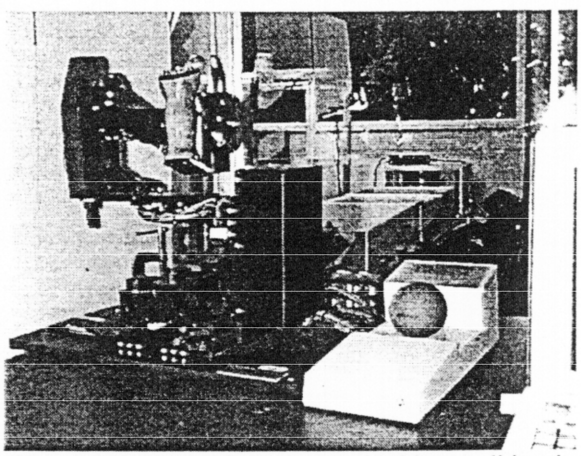

Figure 4. Cybernet CyberImpact beside a traditional force-ball hand controller

The force-reflecting feature was used to implement a hybrid position/rate input mode needed to reduce the amount of reindexing required during operation. Reindexing is required whenever the master control arm runs into a stop prior to the slave arm reaching the desired target in that direction, much the same as making multiple mouse sweeps to move a cursor across a computer screen. Regardless of the scale factor on a mini-master, reindexing is frequently required — more often if the gain is set for finer resolution. By using the force-reflection capability of the hand controller, artificial walls were constructed in the hand controller work volume in all six degrees-of-freedom and just prior to hitting the hard stops. In the free-space of the hand controller, operator input is mapped to an incremental position output. When the artificial wall is encountered, the force the operator is applying against the wall is mapped to a velocity in the direction of, and proportional to, the force on the wall. Hybrid input mode greatly reduced reindexing, improved productivity, and reduced the tedium of using the mini-master. It was the key development the allowed the mini-master to be used efficiently even with a very limited range of motion.

Collection of waste characterization data and selection of different autonomous tasks and operating modes posed a different design challenge. Although MWMF initially was planned to operate with one manipulator arm, a second arm was planned for more advanced demonstrations at a later date. Therefore, it would be quite awkward to switch hand positions from the hand controller to a keyboard or mouse for computer control. Voice recognition was selected after considering that the task vocabulary was limited and well-defined. In addition, the use of voice recognition removed one of the stigmas associated with telerobotics — the keyboard and the associated implication that the operator must be a computer operator or programmer to use the technology. Nuance's CORONA speaker-independent voice recognition and natural language processing software was chosen for our prototype voice interface. A flat-panel X-windows display was used to display the recognized speech, provide confirming messages to the operator prior to initiation of autonomous tasks, and display available menu options.

The CORONA vocabulary and grammar definition mechanisms were very straightforward and the system was impressive in it's ability to adjust to differences in speaker's accents and rates of speech with no operator training. For prototyping purposes, the voice recognition system succeeded in demonstrating that voice is a suitable method for providing operator commands for all routine computer interactions in our task environment. However, the software based system often takes as long as two seconds to complete processing and return the desired command. This response rate is too slow and the final system implementation will likely use one of the available hardware speech processors to accelerate the recognition task. Where very fast response is needed, the pushbuttons on the hand controller will be used instead of voice recognition.

The menu system provided an effective quick-reference for operators just learning the system, but would likely not need to be visible during normal operations. However, the messages confirming how the system interpreted the speech commands were quite important and require little space for display. A heads-up display for this information will likely be pursued for the final system implementation.

IV. RESULTS AND CONCLUSIONS

The purpose of the engineering development and telerobotic prototyping activities supporting the MWMF design was to reduce the technical risk of deploying the technology. The prototyping needed to answer all key design questions was completed in September, 1996. During the one-year design and development effort, much was learned. The control console was discarded after contributing to glare on the viewing window and being replaced with a much more flexible method for holding the required displays; the force-reflecting hand control with hybrid position/rate mode was determined adequate for plant use; the collision detection system was shown to operate at real-time rates on conventional computing platforms including a Motorola 68060 and an SGI workstation; a revised 3D-blob detection system was shown to work at frame-rates; the collision-free path planner was demonstrated to generate most paths in less than 1 second; voice-recognition proved to meet interface function needs, and the required speed improvement identified; and ControlShell real-time performance was validated with all telerobotic components in place. These questions answered, we are prepared to complete final design with confidence that the deployed system will meet all system design requirements.

Integration of the 3D blob-detection and real-time path planning algorithms onto one platform had not been accomplished when the decision was made to not deploy the technology in LLNL's waste management facility. All other elements had been operating as an integrated system (with pre-stored paths) since June, 1996. Since then, the system has been operated by many untrained and non-technical visitors, managers, technicians and students. The system has been shown to be both robust and reliable, with several delicate filtering screens around the sort table still undamaged after attempted assaults by many new robot operators. The core control system components were licensed fee-free to Schilling Robotic Systems for their use in May, 1996. Since that time, Schilling has deployed a telerobotic system with a ControlShell based controller during nuclear reactor maintenance activities abroad.

V. ACKNOWLEDGMENTS

We would like to thank Brad Richardson, the ORNL Robotics and Process Systems Division, and Schilling Robotic Systems for their support and collaboration in the development of ControlShell-based controller technology. Thanks also to the mechanical design team of Paul Densley, George Goers, Tom Churchill and Frank Silva for their technical contributions to the design.

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