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Advanced Robotic Technologies For Transfer At Sandia National Laboratories*

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Introduction

Hazardous operations which have in the past been completed by technicians are under increased scrutiny due to high costs and low productivity associated with providing protective clothing and environments. As a result, remote systems are needed to accomplish many hazardous materials handling tasks such as the clean-up of waste sites in which the exposure of personnel to radiation, chemical, explosive and other hazardous constituents is unacceptable. Traditional remote operations have proven to have very low productivity when compared with unencumbered humans. Computer models augmented by sensing, and structured, modular computing environments are proving effective in automating many unstructured hazardous tasks.

Work at Sandia National Laboratories (SNL) has focused on applying flexible automation (robotics) to meet the needs of the U. S. Department of Energy (USDOE). Dismantling facilities, environmental remediation, and materials handling in changing, hazardous environments lead to many technical challenges. The USDOE need to accomplish the tasks in a faster, safer and cheaper manner influences the approach to robotics. At SNL, faster and cheaper technology development has resulted from creating each needed technology into a generic module that can be quickly integrated into new systems and applied to new needs. Computer planning, monitoring and operator assistance shorten training cycles, reduce errors, and speed execution of operations. Robotic systems that re-use well-understood generic technologies can be much better characterized than robotic systems developed for a particular application, leading to a more reliable and safer systems. Further safety in robotic operations results from use of environmental sensors and knowledge of the task and environment. Collision detection and avoidance is achieved from such sensor integration and model-based control.

This paper discusses selected technologies developed at SNL for use within the USDOE complex that have been or are ready for transfer to government and industrial suppliers. These technologies include sensors, sub-systems, and the design philosophy applied to quickly integrate them into a working robotic system. This paper represents the work of many people at the Intelligent Systems and Robotics Center at SNL, to whom the credit belongs.

Generic Intelligent System Controller Architecture

The diversity of potential robotic tasks within the USDOE requires different combinations of manipulators, tools, sensors, input and feed-back devices. Further, the size and scope of many tasks require teamwork, integrating commercial equipment with advanced

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technologies developed in the laboratories. To facilitate the rapid integration of the diverse equipment and technology modules for specific needs, and to organize the efforts of many commercial and government participants, the need for a common structure was recognized.

The Generic Intelligent System Controller Architecture, or GISC, is a modular approach that combines robots with computer models and sensors to provide intelligent robotic systems[1]. GISC is an agent-based control structure, where supervisory "agents" orchestrate the activities of sub-agents. Figure 1 illustrates the GISC structure.

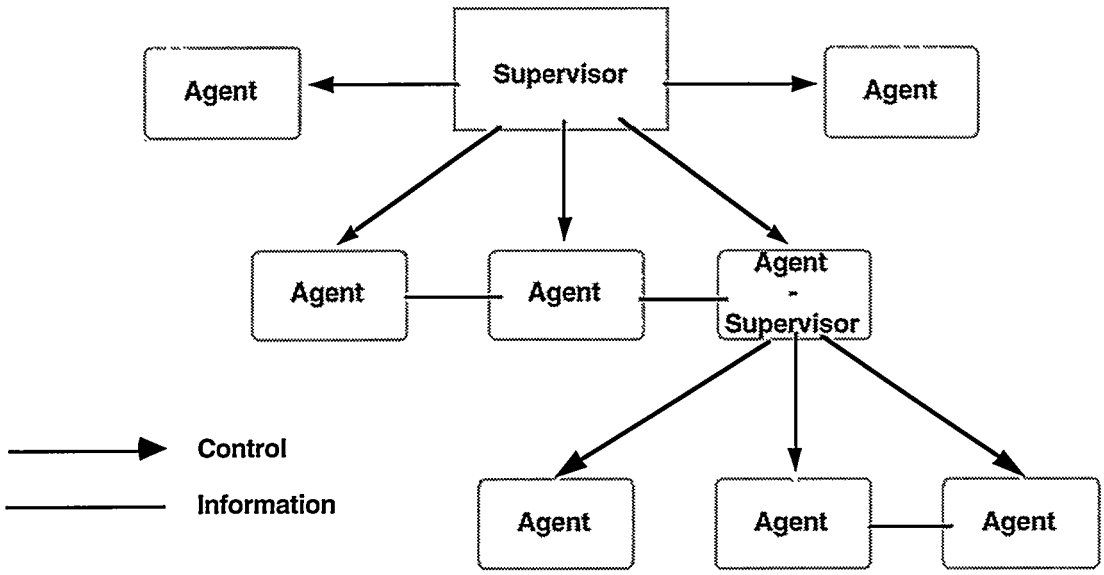


Figure 1. Generic Intelligent System Control (GISC) Architecture

The basic GISC concept is that the instructions passed from the Supervisory Controller are general in nature and that each subsystem is intelligent enough to interpret these generic commands and automatically compile them into device-specific executable commands.

Several agents may comprise the "Supervisor," such as operator input devices, graphics displays, motion planning software modules, and the world model (knowledge base including engineering data, procedures, locations, etc.).

Figure 2 illustrates in greater detail how the interaction of the agents create a Supervisor, and how intelligent sub-systems (sub-agents) such as a robot and its controller can "plug in" to create a customized system.

The Underground Storage Tank (UST) Demonstration at Hanford, Washington, (Figure 3) is a successful example of GISC application. Here, three commercial robots from Schilling, RedZone and SPAR, were integrated with sensor systems and special tooling to map and dismantle a mock-up of an underground tank section.

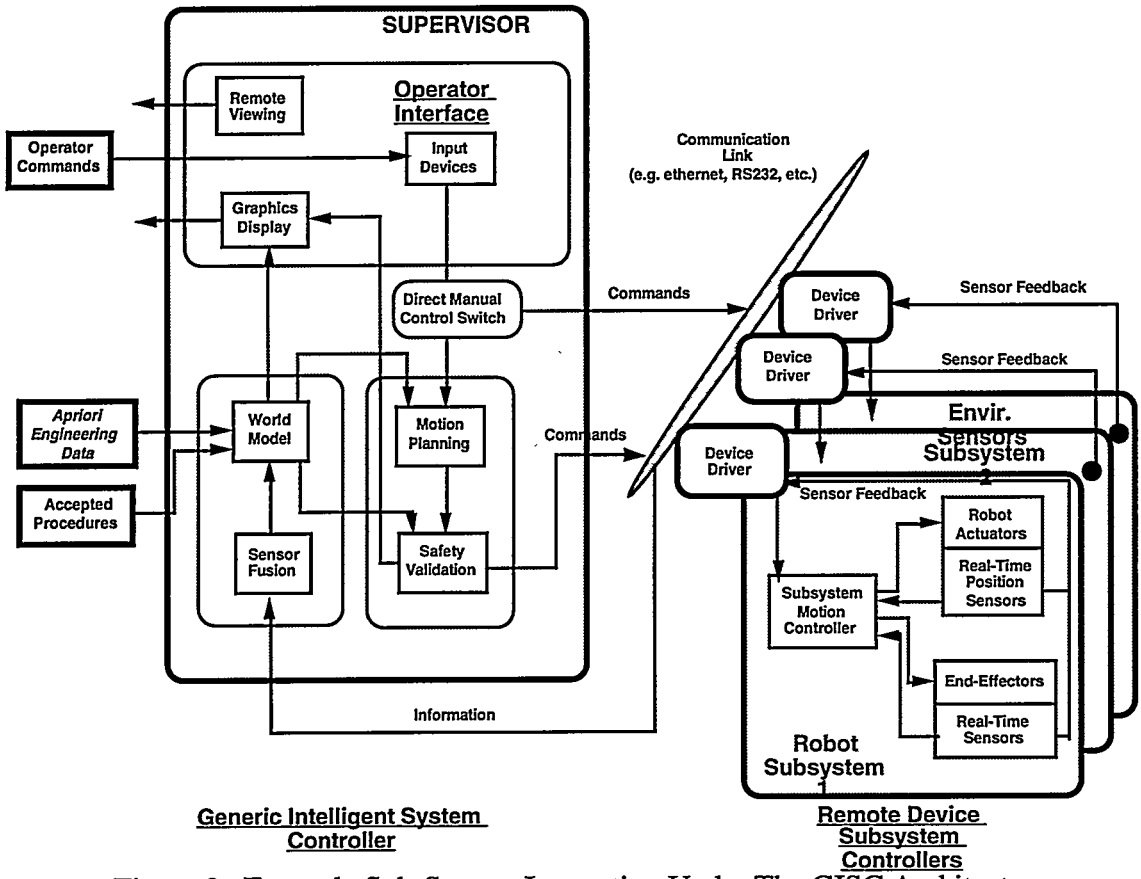


Figure 2. Example Sub-System Interaction Under The GISC Architecture

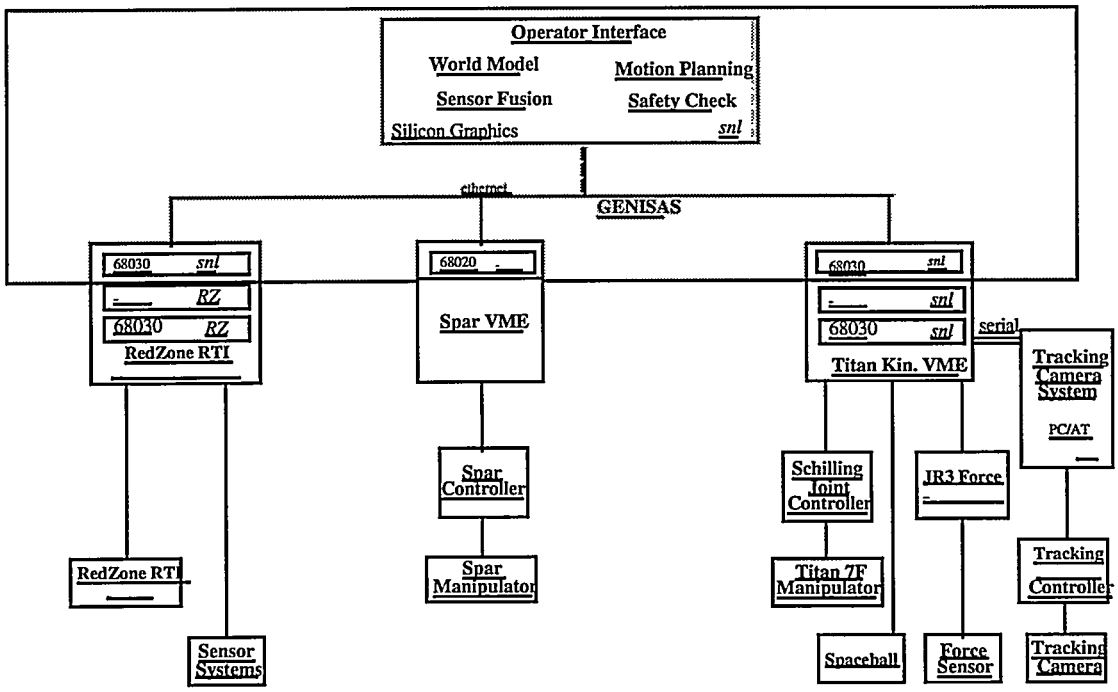


Figure 3. GISC Architecture Applied To An Underground Storage Tank Demonstration

GISC is currently enabling many USDOE laboratories and commercial partners to coordinate and integrate development activities under a standard architecture. In addition to the UST demonstration, a Light-Duty Utility Arm is underdevelopment with industrial support, a Tank Waste Retrieval Arm is being developed at Pacific Northwest Laboratories, RETRVIR (described below) is operating at SNL, Mixed-Waste Operations were demonstrated at Savannah River Site, as was the SWAMI drum inspection robot. All these systems operate under the GISC architecture.

SMART

When building flexible telerobotic systems from different input devices and robots, it is crucial to assure system control stability. The Sequential Modular Architecture for Robotics and Teleoperation (SMART) assures this stability and enables operators, sensors and world models to work together to accomplish a task while preventing a slave robot from damaging either itself or the environment[2]. Under the GISC structure, SMART is an intelligent sub-system that either serves as a robot controller or works in conjunction with the existing robot controller, communicating in real-time with the robot, input and sensor devices.

SMART can be used for any robot that can accept external position set points and with any sensor that can be interfaced to a VME bus. The architecture is both open and modular. Distinct modules are defined for each sensor, actuator, input device and dynamic element. The hardware consists of commercially available CPUs and processor boards running on a VME bus with a UNIX-based operating system. The system is connected to a host processor and a graphics workstation using Ethernet. The software consists of libraries of C-routines. The architecture is parallel and real-time. Modules can run asynchronously, distributed arbitrarily across multiple CPUs and attached processors. SMART uses dynamic interactions between modules to obtain desired behaviors. Servo loops are closed at fixed rates ranging from 100 Hz to 1 kHz.

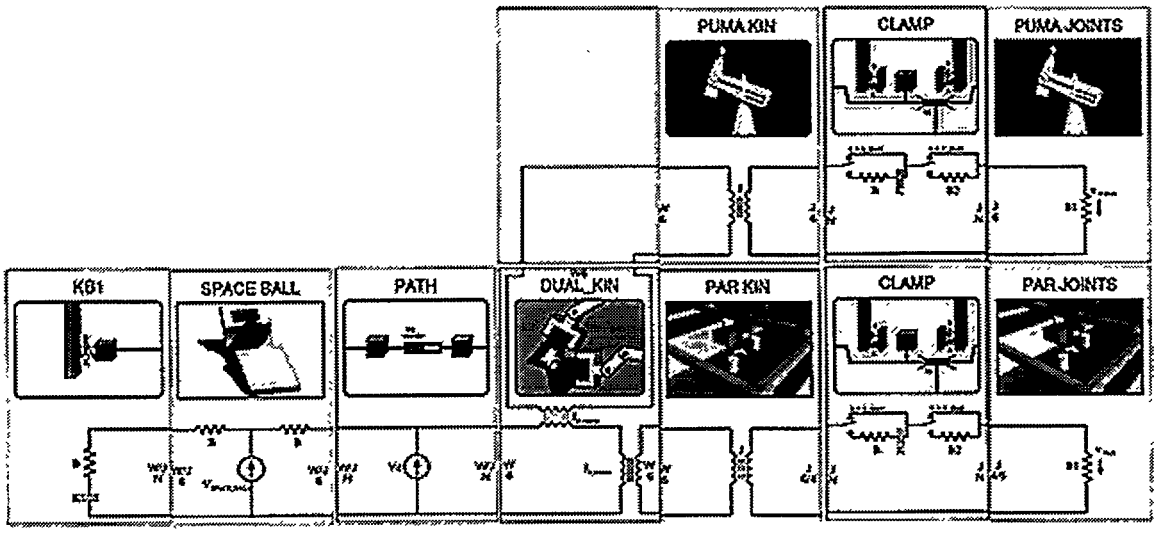


Figure 4. SMART Modules Combine To Form A Stable Control System For Simultaneous Control Of Two Different Robots.

An example of a SMART control system built from SMART modules is illustrated in Figure 4. A system of two different robots with a "spaceball" input device is created with SMART modules. The robots are controlled simultaneously in this configuration.

SMART has been licensed on a non-exclusive basis to Micro Dexterity Systems. Micro Dexterity Systems will use SMART to enable bilateral teleoperation of a micro-positioner for micro-surgery. SMART is under consideration to control a robotic closure and welding system for the USDOE's Multi-Purpose Canister system for containment of spent nuclear fuel. SMART is currently running in nine laboratories at SNL, and has been demonstrated at four DOE sites.

Capacitive Sensor Seam Tracking and Obstacle Avoidance

Capacitive sensors have been developed and successfully integrated into robot systems at SNL to accomplish seam tracking and obstacle avoidance. The sensors produce an electric field between appropriately spaced electrodes. These fields are perturbed by the workpiece, resulting in capacitance changes which can be interpreted and utilized for motion control purposes. Several versions of capacitive sensors exist.

One version, the Multi-Axis Seam Tracking (MAST) sensor, has been designed and successfully applied to manufacture Delta rocket booster engines at Rocketdyne[3]. The engines consist of hundreds of specially-shaped tubes brazed together to form a solid assembly. Figure 5 illustrates the test station with a set of rocket nozzle tubes. A robot arm scans the surface of the nozzle with a MAST sensor, determines the position and orientation of tubes and seams, and automatically generates paths for braze paste dispensing. Application of the robotic system with the MAST sensor at Rocketdyne will reduce current manual processing times by 50%.

The MAST sensor has shown resistance to interference from arc welding, and is currently under consideration for use as a seam tracking sensor for gas tungsten arc welding of the MPC containers described above.

Another capacitive sensor, known as the WHole Arm Protection (WHAP) system[4], is used as a robot "skin," detecting obstacles and preventing collisions (Figure 6). The WHAP consists of SNL-designed and fabricated sensors, and the robot control system that uses the sensors for active or passive control feedback. The sensor technology lends itself to production in quantity and the design parameters to customize the sphere of influence of the sensors have been established. The sensors generate and sense a capacitive field and can therefore detect the presence of many different materials including metals, plastics, and humans.

Figure 5. The Multi-Axis Seam Tracking (MAST) Sensor Determines Tube Seam Location For Rocket Nozzle Brazing.

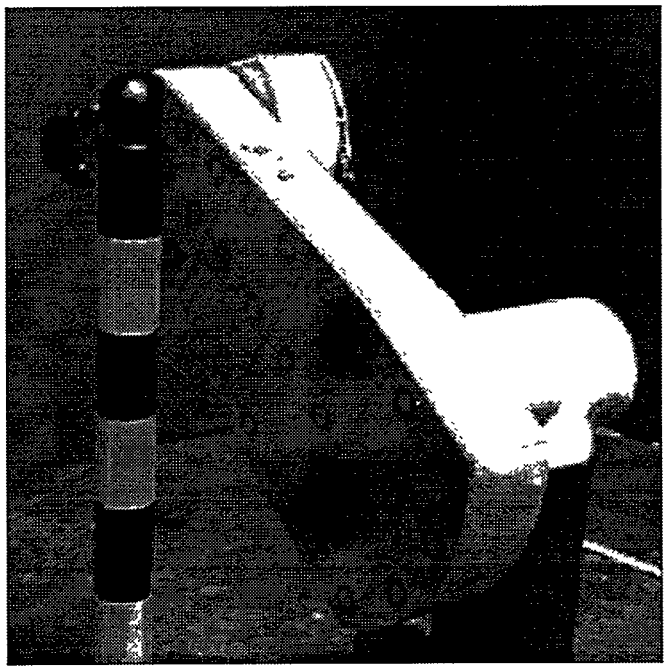


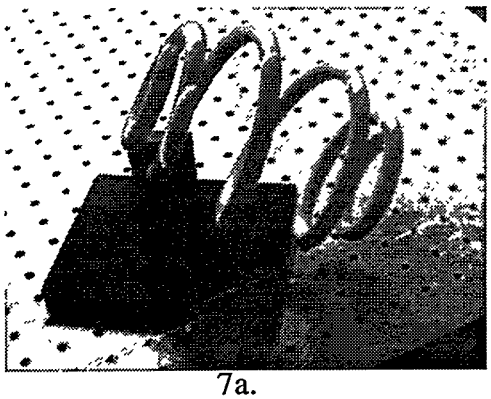
Figure 6. The WHole Arm Protection (WHAP) Sensor Detects Obstacles In The Robot Path, Signaling The Controller And Preventing Collisions During Operation.

The sensors have been integrated into several different robot control systems. Included in the control strategies is a soft Emergency-Stop where if an object is detected by the capacitive sensors the robot is commanded to stop. A reflex control strategy was also developed where the robot would actively move away from a detected obstacle. A third control strategy would prevent the robot from moving closer to an obstacle even when the operator commanded such a move, but would not react to a moving obstacle.

SNL holds the Copyrights for the control software. The sensor and control technologies are available separately or as a complete robot protection system.

Structured Lighting Mapping

Topographical data can be obtained by scanning a surface with a laser and tracking the reflection with a camera (Figure 7). The camera data is converted into topographical maps and can be used to create and update robot world model information. This process is known as Structured Lighting Mapping[5].



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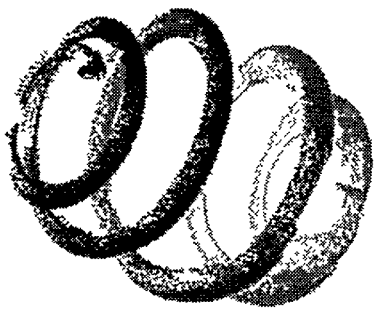

7b.

Figure 7.a. The Structured Lighting System Scans A Spring Surface With Laser Light
Figure 7.b. Spring Surface Topography Is Mapped

The Structured Lighting System is comprised of two or more precision pan and tilt units with encoder feedback. Each pan and tilt unit has a camera and a laser on it so that it can be an emitter or detector. The laser light is passed through cylindrical optics or a diffraction grating that spreads the light in one dimension, creating a line of when the laser light strikes a surface. The pan and tilt units allow the camera and laser to be pointed at the surface to be mapped as well as allowing the laser to be scanned over the surface.

Structured Lighting Mapping has been demonstrated for underground storage tanks at Fernald, Ohio and Hanford, Washington, and for mixed waste operations at Savannah River, South Carolina. At Fernald, a specified thickness of sealant to cover sludge waste in a tank was desired. Excess sealant would require disposal as radioactive waste in the future. Minimization of excess sealant used a stand-alone Structured Lighting system to provide a baseline knowledge of the sludge topography and a means to measure thickness

after sealant application. This work was done in conjunction with Oak Ridge National Laboratory.

At Hanford, Structured Lighting generated a three-dimensional map of a 8 foot by 16 foot mock waste surface in 25 minutes. The map thus generated was then used in the world model of the graphical control interface, allowing the operators to program robots with collision free paths to execute such operations as pipe cutting and rubblizing. This operation was conducted totally under sensor control within the graphical interface software, with no a priori knowledge of the robotic workcell.

At Savannah River, Structured Lighting is used to map a Mixed Waste Operations Workcell containing barrels and glove boxes. The system installed here is 20 times faster than the system installed at Hanford, WA. This map is uploaded to the graphical user interface so that various waste remediation operations can be performed.

The Structured Lighting sensor technology has been transferred to Mechanical Technologies, Inc. in Latham, NY, via a Cooperative Research and Development Agreement (CRADA).

Ultrasonic Pipe Docking

A tool for cutting 2 inch diameter schedule 40 pipe has been configured and demonstrated by SNL as an end-effector[6]. Proper alignment or docking is necessary to prevent transmission of significant forces to a robot arm. Shown in Figure 8, this cutter is equipped with sensors to facilitate automatic docking between the cutter and a pipe.

In the Hanford demonstration, once the geometry within a waste tank was scanned and integrated into the world model, pipe cutting operations were planned and performed. Using the graphical world model representation of the tank environment obtained from structured lighting scans as a guide, operations personnel selected cutting locations along

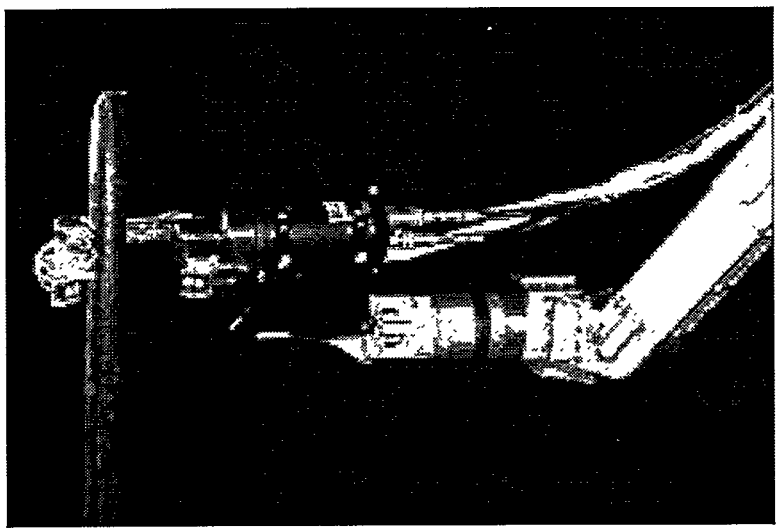

Figure 8. A Hydraulic Pipe Cutting Device Is Fitted With Ultrasonic Sensors To Assist Proper Alignment Of The Tool For Cutting.

lengths of 2 inch pipe residing in the mock-up waste tank. Once specific cutting locations were selected, pipe docking paths for a cutting tool attached to a Schilling Titan II robot were created and downloaded to the Schilling robot controller for execution. These paths contained trajectory information for moving the cutter from an approach position to a docking position at a designated target cutting location. In order to compensate for positional uncertainty between the robot and target cutting location, ultrasonic sensors were mounted on the cutting tool to assist cutter docking. These sensors provided centering error information that was sent to the robot controller in real time. The robot controller used the sensor data to modify docking paths and center the cutter relative to the pipe at the target pipe cutting location.

RETRVIR

SNL has developed the REmote TeleRobotic Vehicle for Intelligent Retrieval (RETRVIR) which integrates model-based, sensor-directed robotic manipulation with a remotely operated vehicle. RETRVIR delivers highly dexterous, sensor-controlled manipulation to remote sites for characterization and retrieval of materials. In particular, two recent focuses of the RETRVIR development activities have been the assembly of a remote instrument platform utilizing interconnecting structural components (Figure 9), and the recovery of buried hazardous wastes.

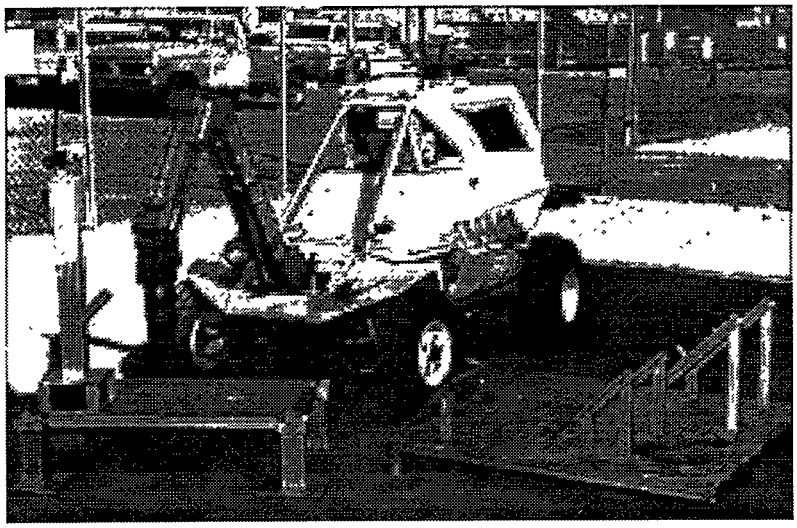

Figure 9. REmote TeleRobotic Vehicle for Intelligent Retrieval (RETRVIR) assembling a remote instrumentation platform structure.

RETRVIR is a development platform that utilizes the GISC structure described above to integrate supervisory, control, and sensory equipment with robotic machinery and a vehicle platform into a functional unit. The robotic arm is a TITAN II manipulator from Schilling Development Company, with a robot controller developed at SNL and now commercially available from Schilling. The vehicle platform is a PILOT all-terrain vehicle from Honda Motor Corporation, modified for remote control.

The GISC structure of the RETRVIR system is shown in Figure 10. A Unix-based supervisory system communicates with an on-board multiprocessor environment

comprised of multiple Motorola 68000 series CPU in a VME backplane, and a VME-based real time base station utilizing VxWorks provides the real-time operating system needed for coordination of the multiple CPUs. An RF ethernet allows communication between the on-board computing system and the base station located in a mobile control room.

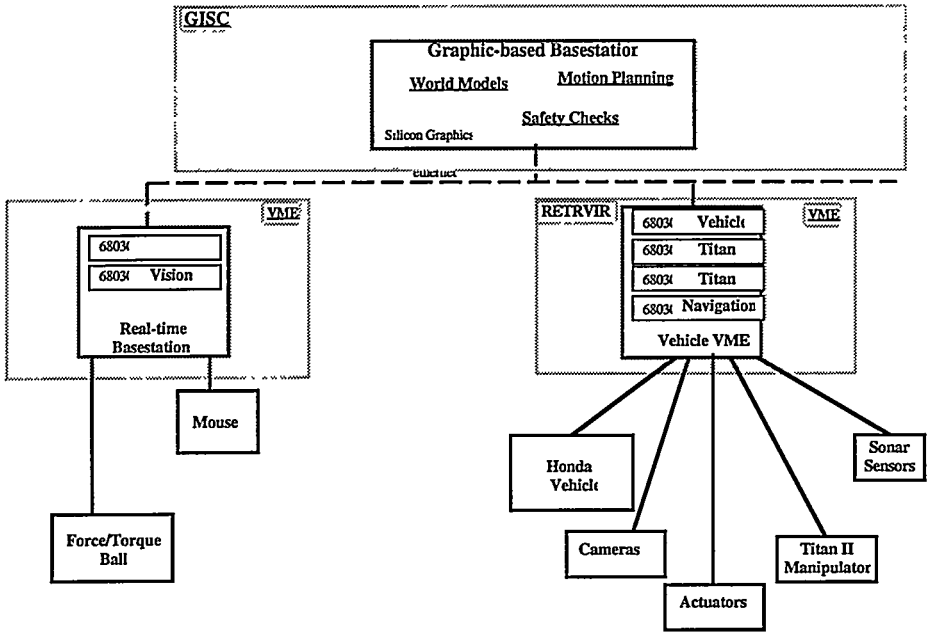

Figure 10. RETRVIR GISC structure

Computer assisted operations allow shared operator/computer control to provide semiautomated manipulation at remote sites as well. For example, an operator may assist in a retrieval operation by placing the cross hairs of two independent closed circuit cameras mounted on RETRVIR on an object to be grasped. A vision system computes the location of the targeted object and automatically moves the manipulator to the object in preparation for grasping. Graphic displays allow the operator to preview all operations prior to execution to allow the operator to ensure safe operation.

The RETRVIR system was recently tasked with the recovery of gas cylinders at an SNL hazardous waste site. The cylinders, some suspected to contain poisonous gasses, were buried for many years in a waste pit. As site remediation began, technicians were also concerned with potential explosions. Wearing protective clothing and respirators against chemicals, as well body armor to protect against explosion could severely limit productivity if manual operations were carried out. RETRVIR excavated the cylinders, placed them in a transport container, and transported them to a safe location for processing, without the need for human presence.

Application of RETRVIR technology is also envisioned for the recovery of unexploded ordinance (UXO). RETRVIR is scheduled for testing of UXO recovery at Jefferson Proving Grounds in September 1994.

Conclusion

Technologies have been developed at SNL for use within the USDOE complex that have been or are ready for transfer to government and industrial suppliers. These technologies all fit within the GISC design structure. Capacitive sensors provide seam tracking, proximity and collision detection for robotic manipulators. Structured Lighting provides a means of mapping work areas into the model-based control systems used in the USDOE complex robotic systems. Pipe-cutting sub-systems benefit from ultrasonic position sensors to cut heavy piping, and have been deployed on robotic equipment in underground storage tank demonstrations. The RETRVIR vehicle system is capable of remote self-deployment, surveying, excavation, structure assembly, and hazardous materials handling. These technologies are all currently available for use in and/or transfer to the commercial sector.

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