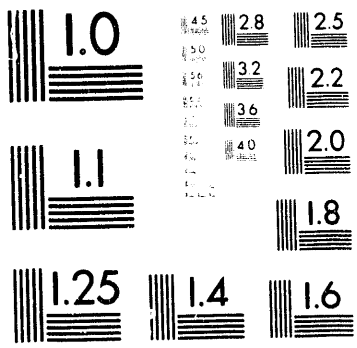
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AUTOMATING THE CONTROL OF ROBOTIC SYSTEMS IN UNSTRUCTURED ENVIRONMENTS*

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Abstract

The U.S. Department of Energy's Office of Technology Development has sponsored the development of generic robotics technologies for application to a wide range of remote systems. Of primary interest is the development of technologies which enable faster, safer, and cheaper cleanup of hazardous waste sites than is possible using conventional human contact or remote manual approaches. The development of model-based sensor-directed robot control approaches supports these goals by developing modular control technologies which reduce the time and cost of development by allowing reuse of control system software. In addition, the use of computer models improves the safety of remote site cleanup by allowing automated error detection and recovery while reducing the time for technology development.

1. Introduction

The Generic Intelligent System Controller (GISC) approach grew out of a series of joint DOE/NIST Workshops initiated in January 1990[1,2] These Workshops were held to determine what generalized approaches should be employed in the development of control system structures to support development of robotic systems for application to DOE waste cleanup problems. The representatives at the Workshops were tasked with identifying a system control environment which would

1. stimulate cooperative team-based robotics system development,
2. facilitate the rapid fielding of integrated robot system demonstrations, and
3. stimulate common approaches to system control within the Robotics Technology Development Program (RTDP).

The first meeting identified the importance of employing modular open architectures. Open software control architectures are critical to stimulation of rapid integration of diverse components and subsystems into functioning robot systems. The second Workshop focused on the importance of distributed multiprocessing computing environments for the control of complex systems. The UNIX operating system was identified as the operating system preferred for software development and VxWorks was identified as the operating system preferred for the real-time subsystem control environment. C and C++ were identified as the preferred programming languages. In addition, the use of graphics operator interfaces to simplify system programming was determined to be highly preferred over conventional keyboard interfaces. Finally, the rapid evolution of computing technology was acknowledged and the need to employ architectures and environments which could easily evolve to take advantage of improvements in computing and robotics technologies was stressed to prevent rapid obsolescence. It was felt to be very important to provide an environment which would both facilitate software development (thus the UNIX based environments) and support the real-time multiprocessing computing environments (VME bus, MC68000 series

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single board CPUs) needed to stimulate the development of advanced robotic systems.

2. Generic System Control

The emphasis in the development of the GISC approach was fu ctional not architectural. As a result, GISC is a strategy for integrating diverse subsystems not a rigid formal architecture. The emphasis, following the results of the NIST/DOE Workshops, was on development of modularity and extensibility. It was felt that modular approaches with well defined interfaces greatly facilitate teaming among diverse organizations since the roles and responsibilities of all contributors are easily identified and understood. In addition, the Workshops emphasized the use of commercial technologies as much as possible to facilitate rapid robot system development. Use of existing technology not only speeds new development but facilitates transfer of the resulting new technology back to the commercial sector since the usefulness of the existing commercial products is increased. At all times during the development of the GISC approach, a goal was to produce a robotic system control environment which facilitated use of advanced robotic technologies by the site remediation technologists.

As shown in Figure 1, GISC coordinates and integrates the operation of diverse subsystems to accomplish complex tasks. GISC's modular approach combines robots with sensors and computer models to provide integrated robotic systems which can automate many waste cleanup tasks and are much safer than conventional remote systems.

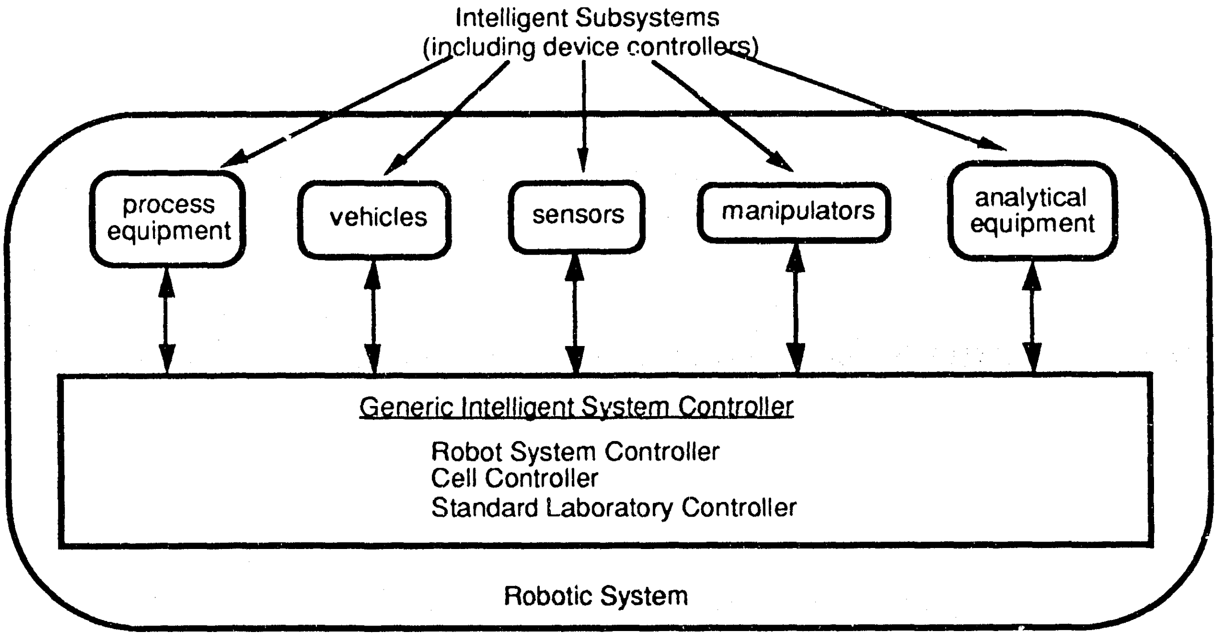

Figure 1
GISC Integrates Diverse Subsystems

GISC is termed an intelligent control system approach because computer models automate much of the system programming and condition the operator interfaces to facilitate correct decision making by a human supervisor. In addition, all operations (both computer planned and operator initiated) are evaluated with respect to the computer models to check for safety. Intelligent decision making algorithms evaluate the known environment represented by a World Model, plan collision free robot motions, and then automatically generate the robot command sequences necessary to execute the desired robot motions. Use of the computer models for error detection and recovery prevents unsafe actions which might, for example, result in collisions. The incorporation of computer models into the GISC approach to robot system control also enables the use of 3-D animated visualization technologies to provide intuitive graphic operator interfaces that allow nonprogrammers to safely program complex tasks.

Figure 2 recasts the diagram of Figure 1 in terms of the major functional blocks of the GISC approach. As indicated, GISC's Supervisor communicates with multiple intelligent subsystems through their respective controllers. Extensive use of computer models (collectively labeled World Model in Figure 2) and sensors allows both operator directed task execution as well as automated operation where appropriate. Direct operator control (*i.e.*, teleoperation) of individual subsystems (see Direct Manual Control Switch in Figure 2) is allowed only on rare occasions during emergency situations or during system development for debug purposes. Only highly skilled remote systems operators are allowed access to this mode of operation.

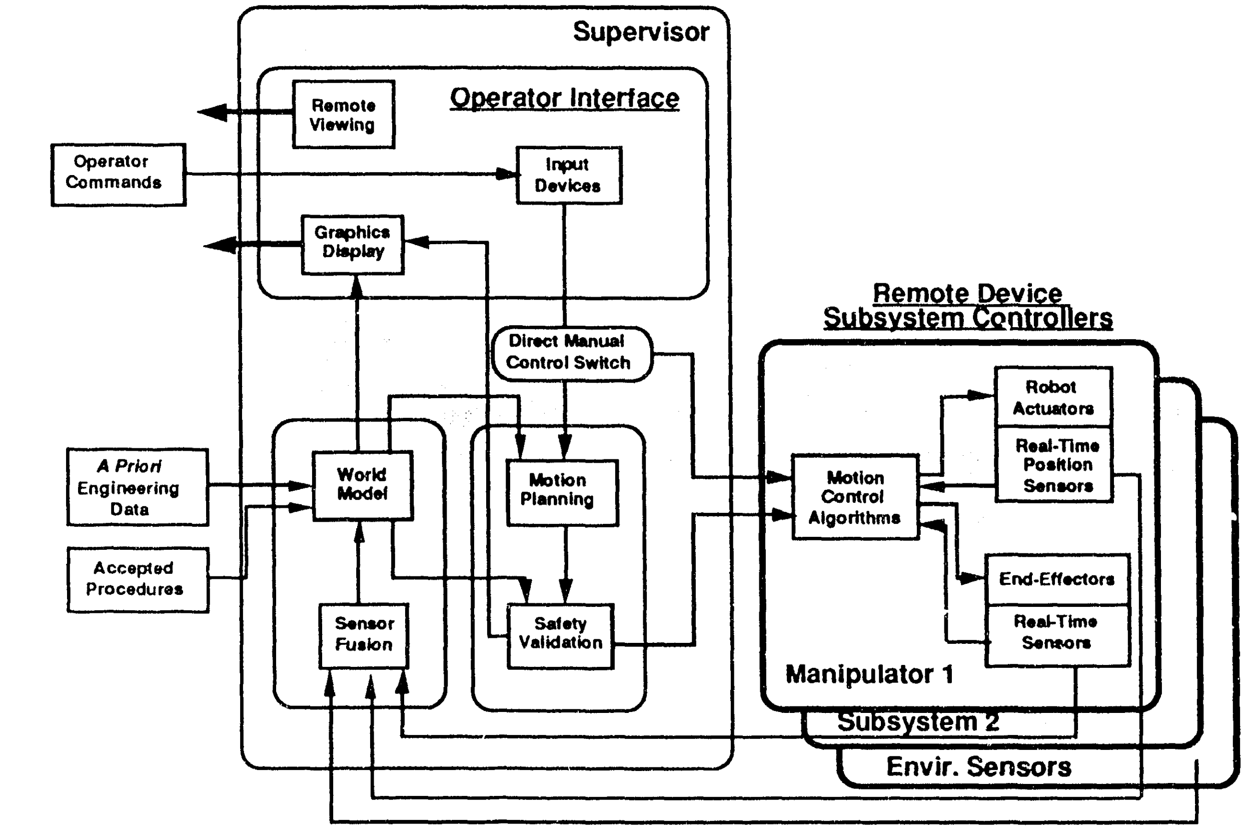

Figure 2

Generic Intelligent System Control Approach

The World Model is at the heart of the GISC approach. The World Model contains the information about the robot system and its environment needed to monitor system operation and to plan the execution of tasks. The World Model is developed by combining *a priori* engineering knowledge of the overall system including information from engineering drawings about known structures in the environment, robot end effectors and tools, and knowledge of proper operating procedures with knowledge of the robot system properties such as kinematics and dynamics. While CAD information of the robot's environment together with the kinematic and dynamic models of the robot and other devices make up the major portion of the World Model, sensors also provide information to the World Model. Sensors determine new static information about the robot's work space which is integrated into the World Model and also provide updates to the World Model as operations are executed. The World Model is thus dynamically updated at all times based upon the most recent sensor information.

Sensor-based mapping of the environment is required to verify and augment the *apriori* engineering knowledge contained in the World Model. A common mapping task, for example, is to determine the location of the surface of the waste in a waste storage tank. Other mapping tasks could involve characterization of the chemical and radiological contaminants at a waste site to allow planning of optimal waste remediation tasks.

Visualization software efficiently communicates the dynamic information in the World Model to the system operator by use of the Graphics Display module of the Operator Interface. Visualization software technologies provide highly intuitive animated graphic displays of the computer's knowledge base thus allowing the operator to easily verify that the World Model is correct and to preview all intended robot movements prior to actual execution. In this way, visualization allows the operator to view what the computer is *thinking*. The close linkage of the World Model with the graphics interface also allows much of the robot motion programming to be done in the graphics environment. Operator directed movement of devices within the graphics interface are automatically compiled into the proper robot commands using information from the World Model. After graphically programming a desired sequence of robot movements, the computer generated programmed movements can be reviewed in the animated graphics interface and modified by the operator if necessary. Once the operator is satisfied that the programmed motions are correct, the commands are communicated to the robotic device for execution. At no time will the computing system allow execution of a programmed operation if the World Model determines that unsafe operation may result.

As shown in Figure 2, all operator commands to the system are checked against the knowledge contained in the World Model to ensure that the command will be executed safely and within the guidelines of any Standard Operating Procedures governing the robot system operation. If the operator's command can be executed safely, the command is communicated to the subsystem Motion Control module. In the case of Figure 2, the Motion Control module contains the real-time system servo control algorithms for movement of the remote robot subsystem. High speed sensing subsystems provide the needed sensory inputs to the robot subsystem motion control algorithms to perform, for example, force controlled interactions with the environment. Real-time sensing also allows in-operation modification of the robot system motions to, for example, prevent collisions with previously unknown obstacles or to allow the robot end effector to track the surface of the waste. It is important to recognize that high speed sensor-based servo-controlled operations are executed within the subsystem controller and not by the higher level GISC environment. This prevents delays in the servo control loop due to bottlenecks in communication and computation. Distributed computing environments as identified in the NIST/DOE Workshops[1,2] are an important feature of the GISC approach to robotic system control. This provides natural modularity and extensibility and enhances the responsiveness of large robotic systems.

Sensors used for real-time control of individual subsystems communicate with the supervisory level GISC models to inform not to control. This provides dynamic updating of the World Model which is critical to the successful use of model-based control environments such as that used in the GISC approach. The updated models are used both to detect possible safety and operational problems as well as to provide the accurate World Models needed for automated planning and programming of new operations. The importance of communicating dynamic sensory information to the GISC World Model must be stressed. Since the World Model is used to validate all commands to the active subsystems, it is important that the World Model contain measured information wherever possible. Use of measured information such as manipulator joint angles will not only provide updated World Models but allow verification that the computer models used by the World Model to automatically program operations accurately represent the motions generated by the subsystem controllers. This is especially important during sensor-based operations when the motion of the manipulator is governed by real-time sensor inputs not precomputed trajectories.

If an operator's command to a robot system is deemed unsafe when examined with respect to the knowledge contained in the World Model, the operator's command is either modified slightly to, for example, allow the robot to avoid a known obstacle, or interrupted completely. If the operator's command is interrupted, the operator is alerted and the reason why the command is thought to be unsafe is communicated to the operator (usually via the Graphics Display).

The most common mode of operation is to graphically display the anticipated robot motions which will result from all commanded robot operations to the operator prior to the operator issuing the final permission for robot system motion. This is an important operational mode since it is not always clear to an operator what the result of a commanded motion might be. Joint limitations in some commercial manipulators, for example, can result in unanticipated motions to achieve what to the operator was a very simple move command. Such unanticipated motions could result in collision if not detected prior to execution.

Automatic robot system operation is also supported by the control system approach shown in Figure 2. It has been demonstrated that many of the repetitive operations associated with waste cleanup can be successfully planned by a computer and executed by a robot system without direct operator involvement. During automated operation, the Motion Planning module uses knowledge contained within the World Model to determine which detailed commands will be sent to the robot system Motion Control module. As in the case of the operator derived system commands, these computer planned robot system operations can be displayed to the operator using the Graphics Display prior to the operator issuing final permission for robot operation. During automated operation, the operator is in a supervisory role monitoring system operation using the Operator Interface Subsystem (including Graphics Display and Remote Viewing). The knowledge within the World Model can also be used, if desired, to automatically adjust the Remote Viewing angles to provide the operator with the best, operation dependent information to complement the Graphics Display.

Notice that to this point, the description of the control system architecture is very general. There has been no discussion of the specific robot used in the waste recovery operations nor of the characteristics of the waste environment. The general control system environment allows variations simply by changing the knowledge contained within the World Model or the Motion Control modules. As understanding of the problem changes, the detailed nature of the individual control system modules may be modified, but the basic GISC structure remains the same.

An important characteristic of the GISC approach is the extensibility of the various modules without requiring changes in the overall system structure. This is particularly important in the area of the robot servo control algorithms comprising the Motion Control module. Initially, motion control of the remote robotic system will most likely be performed using the traditional PID control algorithms adapted to the specific characteristics of the robotic manipulators being used. However, it is anticipated that enhanced servo control modules which, for example, model actuator response may be needed to provide the sensitivity of manipulator positioning needed for many waste cleanup tasks. It is also expected that many of the large manipulator systems used for remediation may oscillate during operation. As these effects are quantified during initial testing and operation, advanced control algorithms which compensate for such oscillations can be developed and integrated into the subsystem Motion Control modules without affecting the overall GISC structure. Thus, the GISC approach encourages advanced development since systems can be updated easily with more advanced technologies as they become available.

3. Use In Prototype Systems

A first implementation of GISC was completed in 1991 and used at Hanford, Washington as part of the Underground Storage Tank Robotics Technology Development Program[3]. The tasks addressed in that first system prototype by the RTDP were mapping of internal structures and waste surfaces in underground storage tanks (USTs) as well as removal of the waste and structures such as piping from the tank both for laboratory analysis and tank cleanup. Both fully automatic and manual robot control technologies are being developed and demonstrated.[3] Computer assistance is employed whenever manual control of the robot is required.

The UST Robotics Testbed at Hanford employs a large commercial Spar Aerospace robot as a high strength positioning system for a dexterous Schilling Titan manipulator. A Remote Tank Inspection (RTI) Robot developed by RedZone Robotics was used to deploy sensors for tank wall inspection operations. Pacific Northwest Laboratory developed a Tracking Camera which, using information from the robot's joint encoders could automatically track the motion of any part (typically the end effector) of the moving manipulators. Both ultrasonic and optical Proximity Sensors were used for localized waste surface detailed mapping and proximity control of the Titan manipulator. Structured Lighting was used to map the waste surface for addition to the World Model prior to the start of robotic operations. Engineering drawings of the testbed served as the *a priori* Engineering Data for the initial World Model. The initial multilaboratory project team members included Westinghouse Hanford Company, Oak Ridge National Laboratory, Pacific Northwest Laboratory, Idaho National Engineering Laboratory, Sandia National Laboratories, as well as representatives from Spar Aerospace and RedZone Robotics.[3,4,5]

The computing structure for this first implementation of the GISC approach is shown in Figure 3 together with the ethernet communication interfaces between the Supervisor and the intelligent subsystems. In all cases the primary interfaces are Motorola 680X0 series CPUs in a VME backplane. These CPUs act as device drivers and interpret the generalized GISC commands and convert them to the commands understood by the individual subsystem controllers. In addition, these VME based interface units also interfaced the ethernet communication

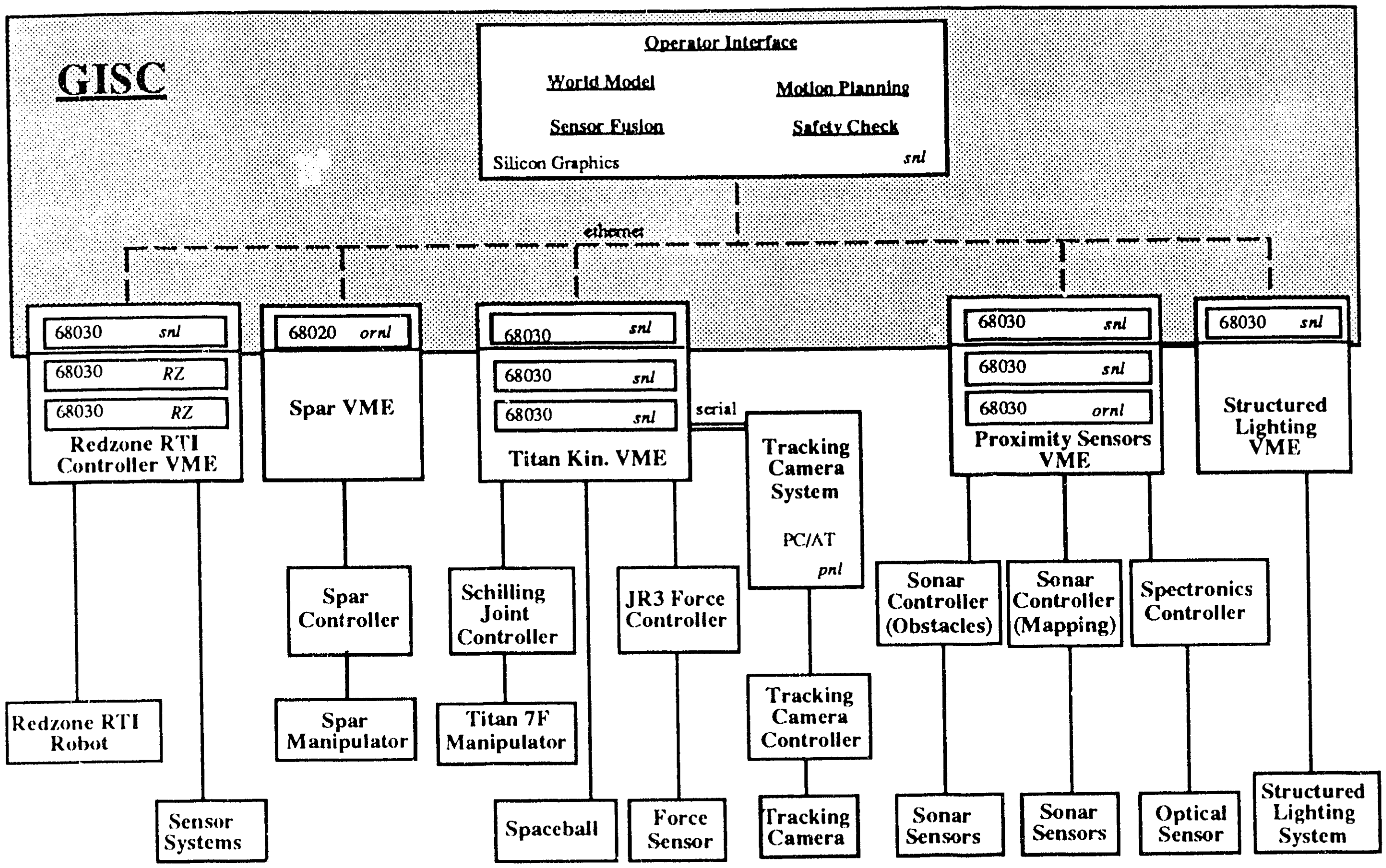

Figure 3
UST Robotics Demonstration -- GISC

system with the subsystem communications required by a specific robotic devices (e.g., RS232 serial communication in the case of the Spar). The VxWorks operating system was used on the VME systems. The equipment outside the box marked GISC represents independent subsystems developed by multiple laboratories with industry. Each has different computing a--- control environments. In one case, the Tracking Camera, an IBM PC/AT was used as the subsystem controller and serial communication was used to interface this subsystem into the overall system. The modularity of the UST Robotics Testbed is apparent as is the ability of the GISC approach to integrate diverse subsystems into a coordinated system addressing key waste cleanup issues.

The Proximity Sensors subsystem in Figure 3 performed two functions. One function of the sonar proximity sensors was to provide high precision maps of the waste surface and vertical piping (risers) within the testbed environment. The Proximity Sensors module performed the statistical correlation of the multiple sonar sensors with location of the Titan manipulator (upon which the sensors were deployed) to compute positional maps. These computed maps were then communicated to the Sensor Fusion module of GISC (see Figure 2) and entered into the World Model. A second function of the proximity sensors was to provide proximity servo control. During proximity servo control of the Titan manipulator, range information was passed directly to the Titan subsystem controller without direct Supervisor involvement (except for the communication software) to allow high speed servo control. Proximity information for servo control could be obtained either from the sonar sensors or the Spectronics optical sensor, both of which were being tested.

The Structured Lighting used a laser based sensing system to develop maps of the waste surface to enable the robot subsystems to safely approach the waste surface for more detailed operations. The Structured Lighting subsystem analyzed all optical data locally and passed only processed map information to GISC to be combined with the initial Engineering Data to provide more complete World Models for automating robot system programming. Thus, the modular structure desired as part of GISC was implemented in a straightforward manner. The modularity enabled multilab teams to work easily together. System integration for this complex systems required less than 10 weeks.

Advanced capabilities resulting from the model-based, sensor-directed GISC approach were recently demonstrated in the Second Underground Storage Tank Robotics Demonstration held in Hanford, WA on November 10, 1992. This second prototype robotic system demonstrated many additional waste retrieval tasks needed for the cleanup of underground storage tanks. The feasibility of automating these tasks was demonstrated by dynamic construction of a World Model of the unstructured task environment based upon sensor information. An important advance in the 1992 Underground Storage Tank Robotics Demonstration was the conversion of sensed data into accurate model information for integration with the World Model. Automation of operations such as the pipe shearing task discussed below significantly reduces the time for task execution while increasing operational safety.[6]

Pipe shearing nicely demonstrated dynamic construction of a complete World Model for use in automating difficult tasks. Structured lighting information representing all surfaces within the robot's work envelop was integrated into the World Model and presented to the operator using the Graphics Display. The operator then interactively positioned a graphic image of a 2-inch Schedule 40 pipe at the location indicated by the structured lighting system. This integrated the actual geometric model of the 2-inch pipe into the World Model at the correct location in the workspace. The operator then indicated in the Graphics Display a location near the image of the pipe to be cut. The GISC Motion Planner (see Figure 2), using knowledge of the location and orientation of the pipe and approved pipe shearing practices, automatically computed the proper tool pickup and robot motions to position the pipe cutter tool near the pipe surface. Once safely in the approach position, real-time ultrasonics were used to dock the hydraulic shear around the pipe and execute the shearing operation. Real-time sensor-directed docking was critical for proper alignment of the shear to ensure that the large forces involved in the pipe shearing operation were not inadvertently transmitted into torque on the pipe which might result in structural damage to the tank. After completion of the shearing operation, the robot automatically returned the hydraulic shear to its storage location in the tool rack.

4. Conclusions

Automated execution of remote tasks in hazardous environments results from integration of computer models and sensors. The highly modular GISC approach facilitates such integration and thus enables rapid prototyping of integrated robotic systems which demonstrate highly intelligent behavior. Extensive use of sensing and computer modeling automates many remote operations resulting in fast, safe remote operations. The structure of the GISC environment facilitates dynamic construction of the World Model which is used to automate remote tasks. Thus, geometrical sensing systems locate unknown surfaces and objects which are then integrated with known information about the work space to provide a complete World Model. When World Model information is coupled with real-time sensor-directed control of a robot, tasks can be accomplished automatically even in unstructured environments. Thus, operations which are slow and potentially hazardous using conventional human contact or remote manual approaches are converted to fast, safe tasks even for inexperienced operators.

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