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A ROBOTIC SYSTEM TO CONDUCT RADIATION AND CONTAMINATION SURVEYS
ON NUCLEAR WASTE TRANSPORT CASKS*

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ABSTRACT

The feasibility of performing numerous spent fuel cask operations using fully integrated robotic systems is under evaluation. Using existing technology, operational and descriptive software and hardware in the form of robotic end effectors are being designed in conjunction with interfacing cask components. A robotic radiation and contamination survey system has been developed and used on mock-up cask hardware to evaluate the impact of such fully automated operations on cask design features and productivity. Based on experience gained from the survey system, numerous health physics operations can be reliably performed with little human intervention using a fully automated system. Such operations can also significantly reduce time requirements for cask-receiving operations.

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1.0 INTRODUCTION

The Nuclear Waste Policy Act (NWPA) of 1982 authorized the U.S. Department of Energy (DOE) to establish a national system for disposing of commercially generated high-level radioactive waste (CHLW) and spent nuclear fuel. The NWPA established the Office of Civilian Radioactive Waste Management (OCRWM) to carry out these activities (NWPA, 1982). In addition, the DOE is responsible for permanently disposing of defense high-level radioactive waste (DHLW) currently in interim storage at several reprocessing sites (Zimmer and Madsen, 1985). Disposal activities include receipt of spent fuel, CHLW, and DHLW from commercial reactors and reprocessing sites; transport to a federal repository where the waste is received and prepared for disposal; and final emplacement of the waste in a deep geologic repository.

The DOE is committed to carrying out these activities in a safe and cost-effective manner, ensuring public and occupational safety while reducing handling and transport costs (Zimmer and Madsen, 1985; DOE, 1986). Development activities are under way to optimize many facets of the transport system, including identifying cask features that will increase waste transport cask productivity by improving cask-handling operations at shipping and receiving facilities. These development activities are consistent with the DOE's efforts to reduce life-cycle costs of the transportation system and to maintain total radiological risks, including public and occupational risks, within the guidelines of the as low as reasonably achievable (ALARA) philosophy (DOE, 1981).

Sandia National Laboratories (SNL) is developing advanced cask-handling techniques and investigating the feasibility of using robotic systems for cask and radioactive waste-handling operations at nuclear waste receiving sites. The primary objectives for these development activities are the following:

- to demonstrate the feasibility of using robotic systems for cask handling tasks, and
- to identify cask design features and operations that strongly affect robotic handling.

A prototype robotic system, the Remote Radiation Survey and Analysis System (RRSAS), has been developed to conduct remote radiation and contamination surveys on nuclear waste transport casks. This report reviews the development work for the RRSAS. Section 2.0 presents background information related to the development of the RRSAS, including cask design development issues, cask-handling operations, early conceptual design work, proof-of-principle testing, and technology development issues for automated cask handling. Section 3.0 presents the details of the RRSAS operations. Section 4.0 summarizes technical achievements of the RRSAS project and includes insights into the technical feasibility of further automating cask operations. Section 4.0 also includes conclusions about the impacts of automated handling on cask designs and waste management systems based on the experience gained from the RRSAS project.

2.0 BACKGROUND

2.1 Cask Development and Design Issues

The efficiency of a nuclear waste transport cask depends primarily on its carrying capacity or payload. Transport cask productivity is defined by the number of high-level waste containers, or spent fuel assemblies, moved per year from a shipping facility to a receiving site. Cask productivity is primarily affected by the carrying capacity and the time spent loading and preparing the cask for shipment, unloading and preparing the cask for return shipment, and transporting a cask between two points. A number of opportunities exist to increase the productivity of the next generation of waste transport casks. This is particularly important since the number of future shipments of spent light water reactor (LWR) fuel to repositories will be substantially greater than current shipments. To date, U.S. shipments over the last 25 years total 6,000 metric tons of uranium (MTU). For comparison, approximately 3,000 MTU of spent fuel will be transported each year when a repository is available.

In the future, casks will also be required to accommodate much older spent fuel than is common today. Age of spent fuel is derived from the time of its removal from the reactor. Current casks are predominantly designed for spent fuel cooled for short time periods, i.e., 180 days out of the reactor. Generally, the increase of older spent fuel shipments and the potential for large increases in the number of spent fuel assemblies, or payload capacity, warrants developing more efficient "new generation" casks. As new casks are developed, private industry is being encouraged to be innovative in designing features to enhance both safety and productivity.

Improving cask productivity reduces life-cycle transportation costs and helps maintain radiological risks within ALARA guidelines* (DOE, 1981). For example, increased cask capacities will reduce the total number of shipments required to transport a given amount of fuel. Fewer shipments will reduce the number of handling operations at shipping and receiving facilities, which, in turn, will decrease total cask-handling time. Improving cask-handling times will reduce the number of casks needed to maintain a specific waste-handling rate. Fewer shipments and lower time requirements for cask-handling operations will likely reduce staffing requirements, as well as capital cost for waste shipping and receiving facilities, and decrease occupational radiological exposure. Fewer shipments will also reduce public radiological exposure. Occupational radiological exposures can also be reduced by removing personnel from the immediate vicinity of a cask and by performing cask-handling operations remotely. Unfortunately, such remote operations historically have resulted in significant increases in the time required to perform cask-handling tasks.

2.2 Times for Cask-Handling Operations

The effect of cask turnaround time on transport cask productivity at shipping and receiving facilities was analyzed (Winson et al., 1980). As shown in Table 2-1, if turnaround times for existing legal weight (LWT) and overweight (OWT) truck casks could be reduced from current requirements of 12 and 16 hours at each facility, respectively, to 4 hours each, cask

Table 2-1

Productivity Increases Associated with
Reduced Cask Turnaround Times (Winson et al., 1980)

	Type of Cask		
	LWT*	OWT**	Rail
Turnaround Time			
Current	12 hours	16 hours	6-8 days
Reduced	4 hours	4 hours	4 days
Productivity Increase	28%	62%	19%

*LWT - Legal weight truck cask.

**OWT - Overweight truck cask.

productivity would increase approximately 28 and 62 percent, respectively (Winson et al., 1980). If the rail cask turnaround time at each facility could be reduced from 6 to 8 days, to 4 days, productivity would increase approximately 19 percent. The lower increase for rail is due to more dominant in-transport factors. In terms of costs, one analysis indicates that a 4- to 8-hour reduction in truck and rail cask turnaround times, respectively, could reduce life-cycle transportation costs (excluding facility capital costs) considerably (Shirley, 1983).

While these analyses consider only current generation transport casks, the potential effects of productivity increases are equally applicable to future generation casks. With their projected higher capacities, future generation casks will have even greater potential for increased productivity (Sanders et al., 1987). Performance goals for future generation spent fuel transport casks require turnaround times of 8 hours for truck casks and 4 days for rail casks (DOE, 1986).

2.3 Occupational Exposures Resulting From Cask-Handling Operations

To accommodate the large number of shipments expected at repositories in the future while maintaining occupational exposures within ALARA guidelines, significant changes in waste-handling methods are needed. An early analysis has been conducted to evaluate several concepts for reducing radiological exposure. Three general recommendations for reducing exposures have been derived: maximize cask shielding, maximize facility shielding, and implement remote-handling techniques (Shirley, 1983).

A more recent ALARA analysis evaluates several alternative methods for reducing occupational exposures from spent fuel transport (Schneider et al., 1987). Radiation doses resulting from cask-handling operations at a postulated reference repository are estimated by analyzing hypothetical receiving and handling facilities. Estimates of the distances between the cask surface and operating crew members during handling activities are based on current cask-handling practices. Contact-handling dose estimates for these activities are based on near-cask dose rates and background area dose rates for typical cask-handling areas, staffing and time estimates representative of current experience, and the expected location of workers relative to the casks. All cask-handling activities are assumed to be accomplished with conventional equipment and procedures.

The facility is assumed to receive shipments 24 hours a day, 7 days a week. Assuming continuous cask operations, estimates of cask turnaround time at the facility range from 14.6 hours for a truck cask containing pressurized water reactor (PWR) fuel assemblies, to 16.3 hours for a truck cask containing boiling water reactor (BWR) fuel assemblies. Rail cask turnaround estimates are 21.6 hours for a PWR cask to 30.1 hours for a BWR cask. The average waiting times for casks outside the receiving and handling building are estimated at 14 hours for each truck cask and 20 hours for each rail cask.

Specific handling activities considered in the ALARA analysis are illustrated by Schneider et al. (1987). Upon receipt, the cask and transport vehicle are inspected at the repository's outside security gate. They are then transported to and from a queuing area and then to a wash-down area where they are washed and dried before moving to the receiving and handling area. While in the wash-down area, a health physics survey is performed on cask enclosures, tiedowns, and impact limiters. The cask is then removed from the transport vehicle, placed on a mobile cart, and moved into the handling room. Activities in the handling room include pressure and cover gas testing, outer lid removal, and mating to a hot cell port. A lifting adapter for the inner lid and a contamination barrier adapter are also installed at this time.

In the hot cell, several remote cask operations are performed, including unloading and internal cavity inspection and cleaning. Unloaded spent fuel assemblies, or high-level waste canisters, are placed into temporary storage cells within the hot cell.

The empty cask is then prepared for shipment by reversing the above process. Closure lids are installed, the cask exterior is decontaminated, and the cask is placed on the transport vehicle. The cask tiedowns, impact limiters, and personnel barrier are reinstalled, and the vehicle is prepared for departure.

Only a few of the above activities account for approximately 90 percent of the occupational dose, as illustrated in Table 2-2. For example, the activities performed in the handling room to prepare the cask for unloading account for 67 to 75 percent of the collective dose received by repository cask-handling workers. Removing closure lid bolts contributes most to the total collective dose received by workers: 36 percent per truck cask

Table 2-2

Contributions of Various Cask-Handling Activities to
Total Repository Occupational Dose (Schneider et al., 1987)

Activity	Contribution to Total Dose (%)
<u>Handling Room</u>	
Closure work, gas/pressure testing, installing contamination and lifting system	67-75
Removing closure lid bolts (included in above activities)	[36 (truck)] [43 (rail)]
<u>Preparation Tasks</u>	
Health-physics surveys, removing impact limiters, removing tiedowns	17-19
<u>Cleaning, Monitoring, Inspection,</u> <u>Cask Movement</u>	3-11

(100 person-mrem) and 43 percent per rail cask (200 person-mrem). Other preparation tasks, such as health-physics surveys, removing impact limiters, and removing tiedowns, will contribute 17 to 19 percent of the collective dose to repository workers (54 person-mrem for each truck cask and 79 person-mrem for each rail cask). Cleaning, monitoring, inspection, and cask movement tasks account for most of the remainder. As shown in Table 2-2, these tasks result in 95 to 97 percent of the collective occupational dose at the repository for truck and rail cask handling, respectively.

The total operational dose per cask load is approximately 280 person-mrem per PWR or BWR truck cask load (approximately 300 person-mrem/MTU spent fuel). The dose is approximately 465 person-mrem per PWR or BWR rail cask load (approximately 70 person-mrem/MTU spent fuel). One to two percent of the total dose results from background radiation doses (i.e., from other site radiation sources) in the work area.

These reference repository analyses indicate a relatively small number of repository personnel could receive average individual doses as a result of cask-handling operations as large as 13 person-rem/yr, and the average for each worker could be approximately 3.7 person-rem/yr. This is well above the 1 person-rem/yr ALARA objective for an individual worker.

2.4 Remote Cask Handling

Remote cask-handling techniques are being considered to reduce these occupational exposure levels at a repository. The traditional means of handling materials remotely requires master/slave manipulators, in which a remote mechanical manipulator (the slave) is directly coupled to a mechanism (the master) controlled by the operator (Figure 2-1). The slave manipulator essentially repeats the master's movements exactly. Due to the reduced degree of freedom of master/slave devices and environmental sensing limitations, remote manipulation using such devices is difficult even for experienced operators and, depending on the complexity of the system, can take 3 to 15 times as long as manual operations for identical tasks (Strip, 1987). As a result, interest in developing programmable devices, or robots, for remote-handling operations has increased.

Development has been proceeding since 1983 on advanced methods for performing high-level waste cask operations in radioactive waste shipping and receiving facilities. In 1983, a conceptual evaluation of remote-handling equipment and procedures for cask shipping and receiving operations was initiated by SNL and Hanford Engineering and Development Laboratory (HEDL). This effort concluded that worker exposures can be significantly reduced if such remote-handling systems are developed and used to perform what typically have been hands-on tasks (Yount and Berger, 1984). The evaluation determined that if commercial robots were incorporated into a remote-handling system, worker exposure could be reduced to acceptable levels while maintaining or possibly increasing material throughput.

2.4.1 Proof-of-Principle Experiment

To substantiate the conclusions drawn from conceptual analyses, a limited proof-of-principle experiment was initiated at HEDL in 1984 to test the applicability of robotic systems to waste-handling operations (Berger, Gneiting, and Sanders, 1986). An available commercial robot system has been used to evaluate whether a variety of cask operations could be automated using existing technology and whether a robot system could be used in a master/slave control to respond to unstructured, off-normal events.

A pedestal-mounted commercial robot (Figure 2-2) has been modified for man-in-the-loop control and used to perform selected cask-handling activities. For the demonstration, a full-scale carbon steel mock-up of a DHLW cask (Figure 2-3) has been built, complete with functioning seals and captive closure bolts (Madsen et al., 1987). Also, a nonradioactive DHLW canister (Figure 2-3) has been obtained for cask-unloading operations. A shipping skid with captive hinged tiedowns has been fabricated to simulate features that could be designed into a dedicated trailer.

To accommodate unplanned events, the robot's standard teach pendant has been replaced with a more functional joystick controller. The joystick allows the operator to use natural motions rather than push buttons to control robot movements, making manual control easier. A control station has been developed that incorporates the joystick controller, a microprocessor, the closed-circuit television monitors, a remote crane control pendant, and a

Figure 2-1. Master/Slave Manipulators

Figure 2-2. Pedestal-M
Testing (B

Figure 2-3. Full-Scale DHLW Truck Cask and Canister (Madsen et al., 1987)

programmable controller. Dual three-degree-of-freedom joysticks are used to position and orient the tools used for specific operations.

A communications package has also been developed to interface the robot controller with a microprocessor. The package is necessary to establish a computer communications link and transfer data to and from the robot controller. Included in the package is the capability to store process data and adjust the coordinates of cask features as necessary, based on spatial reference points. Because the heavy cask could not be exactly fixed in a well-defined position, reference points on the cask are determined manually with the robot in a manipulator mode. Once this is accomplished, all other coordinates of the cask features relative to the robot are automatically determined.

The DHLW cask has an outer lid that functions only as a dust cover. A lifting fixture has been designed for handling the cask dust cover. The fixture also provides reaction points for the torque wrench (features against which the wrench could rest to absorb the torques) during dust cover fastening or unfastening operations.

During the demonstration, the DHLW cask mock-up is removed from the shipping skid and placed into a vertical support fixture that simulates a facility cask cart. Cask location has been determined by establishing reference point coordinates on the dust cover and the side of the cask by touching those points. The dust cover is then removed, using a gripper end effector and a lifting fixture. The cask mock-up is then prepared for unloading, using the robot under both master/slave and automatic, preprogrammed control. A gas sampling operation is simulated, and the bolts on the cask lid are loosened. The bolts are spring-captured and remain fixed to the lid. The closure and the DHLW waste canister are removed, using a grapple and a remotely operated crane, followed by reinstallation to simulate a loading operation. Finally, the robot is used to reverse the operational procedure.

The demonstration is conducted using simplified laboratory systems. All operations are conducted with closed-circuit television and no direct viewing, which represents a worst-case situation. Even with these limitations, the proof-of-principle test successfully demonstrates several remote-handling operations for a waste transport cask. While the operations are slow, the feasibility of performing all cask lifting, preparation, and unloading operations from a single control station using remote controls and viewing is demonstrated.

2.4.2 Experiment Results

A principal benefit of the proof-of-principle demonstration is the data collected which allowed a comparison of actual operating times with those predicted by the initial conceptual analyses (Yount and Berger, 1984). Operating times derived in the conceptual analysis are predicted, assuming enhanced robotic equipment, software, and programmable manipulators are available and comparable to those used in the proof-of-principle experiment. This analysis predicts that such equipment could reduce the total cask operating times by approximately 30 percent of current manual requirements

(Berger et al., 1986). In addition, it is predicted that a fully remote system could reduce personnel exposure to near zero for normal operations.

The operating times obtained during proof-of-principle testing is in close agreement with the operating times predicted by the conceptual analysis. Because the proof-of-principle experiment employs standard commercial equipment, the values predicted in the conceptual analysis are conservative. This comparison is illustrated in Figure 2-4.

The information obtained during the proof-of-principle demonstration has been used to estimate the impact of advanced handling methods on the design and operation of shipping casks (Berger et al., 1986). Two important conclusions about the technical feasibility of using currently available robotic systems for remote cask-handling activities have resulted from the proof-of-principle testing: (1) man-in-the-loop control of lifting, moving, and manipulation activities could result in handling time requirements in excess of similar contact operations and the need for rigid structures for cask components and equipment; and (2) the restriction of remote-handling methods to currently available commercial technology could result in significant cask design, fixturing, and tooling impacts.

2.5 Technology Development Issues for Remote Cask Handling

While robot control technology is limited in the commercial sector, applicable advanced technology is rapidly being developed in the research and development sector. Commercially available robot control technology typically restricts robot operations to repetitious movements to and from previously programmed locations. These locations must be rigidly fixed in the robot workspace.

Teaching, the most common mode of robot programming, involves moving the end point of the robot manipulator under operator control to a location in the environment and storing that position in the robot's computer memory. Manual programming of robot trajectories (paths through the environment) is normally accomplished using a teach pendant, or joystick, that allows the operator to move the robot to various work points. From these points, the robot can be commanded to move to other taught points.

Usually, the robot workspace must be rigidly structured by jigs and fixtures to ensure that the work pieces always have the position and orientation expected by the preprogrammed robot. Often this careful fixturing of work pieces may not be sufficient for certain robotic activities which require careful contact with objects. A robot never returns exactly to taught locations. The position error that occurs when a robot fails to exactly return to a taught location is the robot's repeatability. Typical repeatabilities for high-quality robots range from ± 0.010 to ± 0.001 in. Position errors of this magnitude can seriously affect a robot's ability to accurately and safely contact an object, such as a cask, during radiological swiping operations (Griesmeyer and Thunborg, 1988).

If a robot is commanded to return to a previously taught location where it was touching the desired point, the robot may, in fact, not contact the object. This would occur if the robot repeatability resulted in it moving to

Figure 2-4. A Comparison of Expected Cask-Handling Times Based on Current Experience and Predictions Derived From Conceptual Analysis and Proof-of-Principle Experiments (Berger, Gneiting, and Sanders, 1986)

a point slightly above, but not in contact with, the surface. Such action during some cask operations would be unacceptable.

Similarly, if a robot tried to return to a previously taught surface point on a rigid object, but instead moved to a point beneath the surface due to poor repeatability, large forces would be generated. This could lead to damage of the object or the robot.

Thus, operations in which the robot must make contact with objects are best performed using force control. During force control, the robot moves to achieve a desired force and a desired position. Force-controlled robots are designed to comply with forces encountered, and such control is frequently termed active compliance.

Robot compliance can also be obtained by integrating substances, such as springs and foam rubber, that deform under force. Thus, when the robot contacts an object, the compliant substance deforms slightly, acts as a shock absorber, and forces on the robot and object increase slowly. This type of robot compliance accommodates small robot positioning errors and is termed passive compliance. Passive compliance occurs when forces generated upon contact are not actively controlled to achieve a desired force; contact forces are simply absorbed by the compliant substance.

Force-control research has shown the feasibility of using robots to make controlled contact with objects (see Appendix A). Most implementations of force control in robots employ a combination of active and passive compliance, termed stiffness control. In stiffness control, the known characteristics of passive compliance are employed to determine the appropriate move by the robot to achieve the desired force. Thus, if the robot is contacting a surface with a resulting force, the known stiffness coefficient of the compliant material is used to predict the amount of robot movement required to achieve the desired force. Typically, the stiffness of the compliant material selected is matched to the robot's position control characteristics to provide responsive, active force control for the robot.

Unfortunately, commercial force-controlled robots are currently unavailable. However, advanced research robots have demonstrated the feasibility of force control. In addition, these advanced systems have shown the feasibility of using other sensors, such as vision, for servo control of robots in general. With restricted personnel access to robot workspaces in nuclear environments, the manual teaching approach to robot programming is difficult. Such sensor-based servo control would allow robots to sense objects in the environment and respond to them without direct operator intervention.

Current commercial controllers often must be modified to implement sensor feedback. However, conversations with selected robot manufacturers, such as Adept, CIMCORP, and Cincinnati Milcronic, indicate that future controllers may provide for sensor feedback incorporation (Griesmeyer and Thunborg, 1988).

In advanced robotic applications, the robot control functions will be integrated primarily through supervisory computers using models of the robots and their environment, i.e., model-based control. Typically, in research

robotic systems currently under development, several computers external to the robot controller are provided to allow for interrogation of sensors, collection and storage of data, coordination of the robot system with other process flows, and operator interface with the system. Sensor information is used to monitor system operation and to provide updates that are sent to the robot controller; this process provides a form of sensor-based servo control.

Model-based control of robots with sensor feedback requires less structure in the environment in the form of jigs and fixtures (see Appendix C). Using a computing system to provide sensor interpretation can, in some instances, allow an existing commercial robot to perform complex tasks requiring the robot to adapt to its environment during task execution. In addition, the robot can recognize and respond to off-normal conditions, resulting in increased system efficiency and safety.

The procedures and tools necessary to perform cask operations are generally developed by the cask designer; the user is then trained to use these procedures and tools. However, for advanced robotic cask-handling applications, procedures and operational descriptions must be integrated into the software control system of the receiving facility. This requires that cask descriptive software, which contains digitized coordinates of features and mathematical descriptions and definitions of surfaces, be of approximately the same level of detail as the final drawings for the hardware.

2.6 An Approach to Evaluating Advanced Remote Cask-Handling Technology

In 1984, SNL initiated a comprehensive effort to integrate advancing robotics technology with cask-handling feasibility assessments. This advanced technology is also transferred to private industry to ensure availability for actual repository operations.

An experimental approach is being used to evaluate specific cask operations; the RRSAS has been the first test of this approach. Using existing technology, operational and descriptive software and hardware in the form of robotic end effectors are designed in conjunction with the interfacing cask component design. Software and hardware requirements are being developed for remotely identifying a cask or component, establishing the cask's position in three-dimensional space, and integrating a software description of the cask, its components, and contents with operational features and sensory feedback control systems. Conceptual designs of specific cask features, operating software, and end effectors for performing these operations are developed and tested in actual feasibility demonstrations.

Resulting design constraints for cask and robot system interfaces are incorporated into cask interface specifications (Griesmeyer and Thunborg, 1988). Handling times for specific operations are recorded and implemented into a data base to correlate expected cask turnaround times and exposure estimates with specific design features for future system trade-off analyses.

The priority of addressing specific cask operations was determined by (1) the potential benefit in time and exposure reductions, (2) the availability of applicable technology, and (3) the applicability of the technology required for a specific operation or series of operations to subsequent

feasibility evaluations of other operations (Strip, 1987). Since health-physics operations account for a significant portion of worker dose during cask-handling operations, and automation of such activities requires numerous capabilities that apply to virtually all cask operations (Griesmeyer and Thunborg, 1988), the RRSAS project was initiated to address radiation and contamination surveys on waste transport casks. The balance of this report describes and summarizes the achievements of the RRSAS.

3.0 RRSAS DESCRIPTION

As part of cask-handling operations at nuclear waste repositories, workers will perform two types of radiation surveys. A noncontact energy survey slowly moves a radiation counter system near the cask's surface to measure neutron and gamma radiation originating from the cask's contents. A second particulate contamination survey, or swiping, wipes the cask with filter paper to remove particles from the cask's surface. The filter paper is then placed in a special instrument to measure any alpha, beta, and gamma radiation originating from any contamination by radioactive particles present on the cask's surface.

Occupational radiation exposure can be substantially reduced if radiation and contamination surveys are performed remotely, because manual surveys require long personnel exposure times (see Section 2.3). Also, swiping is not a repeatable operation when performed by humans. Robotic systems, however, can standardize swipe parameters, such as contact area and force. In addition, robotic control systems can automatically maintain accurate records of where swipes are performed on the cask surface and the contamination level at that location. Finally, computer analysis of the radiation survey results can be accomplished quickly; the results are automatically correlated with the cask model, operational history, and operational limits. This process simplifies records maintenance and improves quality assurance. Also, task results can be immediately displayed graphically to inform operations personnel of survey results.

The RRSAS was developed to examine the relationship between cask design and the use of robots for conducting noncontact and swiping surveys on nuclear waste transport casks. The complete system, shown in Figure 3-1, consists of a CIMCORP XR®* 6100 gantry robot, modified for force-controlled operation. This prototype robotic system performs five major tasks:

(1) determines the cask's location after delivery in relation to the robot's workspace, (2) identifies the cask and automatically formulates a comprehensive survey plan, based on cask contents, the results of past radiation and contamination surveys, and the results of random generation of survey locations; (3) performs a remote visual inspection of the cask for mechanical damage; (4) executes contamination and radiation surveys of the cask exterior; and (5) analyzes and presents survey results to the operator during system operation.

The following sections review the tasks executed by the RRSAS and the equipment required to perform those operations. Detailed, technical descriptions of the RRSAS and specific subsystems are contained in the appendices. The system control approach is discussed, and the results of RRSAS operations are also reviewed.

3.1 Cask Location

Once a cask has been delivered, the RRSAS automatically determines the position and orientation of the cask with a computer vision subsystem (see Appendix B). Design specifications for future nuclear waste repositories provide that a driver deliver the shipping cask and transporter to a position

*XR® is a registered trademark of CIMCORP Inc.

Figure 3-1. Remote Radiation Survey and Analysis System

under the gantry robot. An operator manually enters the basic cask type into the supervisory computer, thereby providing the robot with the approximate location of known visual reference points on the cask surface. The system handles up to 15 basic cask designs. The robot then positions itself to allow its cameras to locate the visual reference points and, hence, determines the cask's location with respect to the robot.

The RRSAS uses two cameras mounted on the robot's vertical mast to determine the three-dimensional location of each visual feature, such as the square lugs shown in Figure 3-2. The cameras allow the computer system to triangulate and, thus, compute the three-dimensional location of each visual feature. By locating two visual reference points on the near side of the cask and one point on the far side, the RRSAS can determine the location and orientation of the cask to within 0.060 in. The computer vision system automatically corrects for changes in illumination error; carefully controlled lighting is not required.

The system also compares the distance between the visual reference points on the cask with distances contained in a computer model of the cask. If errors are found, it repeats that portion of the computer vision task automatically, without operator intervention.

3.2 Cask Identification

The specific radiation survey to be conducted on each cask depends on its contents and history; therefore, each cask must be associated with software data bases identifying this information. The RRSAS uses a commercial bar code reader, which is similar to those used in grocery stores, to scan a bar code on the end of the cask (Figure 3-3). The supervisory computer then retrieves from memory a mathematical description of the cask, which is a computer-aided design (CAD) model, as well as a record of the cask's history and contents. The computer then develops a detailed survey plan based on this information. If the cask history reveals previous hot spots, i.e., areas with higher-than-normal radiation or contamination levels, these points are selected for close evaluation.

3.3 Remote Visual Inspection and Radiation Survey

The first phase of the survey performed by the RRSAS is the noncontact radiation survey. Visual inspection of the cask for mechanical damage is combined with the radiation survey. The robot uses a tool consisting of a radiation detector and a closed-circuit video camera (Figure 3-4). Noncontact radiation surveys are performed using a Geiger-Muller radiation counter to scan the cask surface. The closed-circuit video image is displayed to the operator in the control room. The operator checks for physical damage to the cask and for any unauthorized objects that may have been placed on the cask transporter. The amount of detected radiation is promptly displayed to the operator using computer graphics. Figure 3-5 shows the RRSAS display of noncontact radiation survey results after a typical cask survey. The computer remembers the locations of all survey points and can automatically return for a detailed resurvey, if desired.

Health physicists at SNL determined the proper survey scan rate. Currently, the noncontact radiation scan rate is 6 in./s. Linear scans are

Figure 3-2. Locating the Transport Cask With Computer Vision

Figure 3-3. Identifying the Transport Cask With a Bar Code Reader

Figure 3-4. Noncontact Radiation Detection

Figure 3-5. Computer Presentation of Noncontact Radiation Survey Results

performed at seven locations around the cask to demonstrate a complete radiation survey. After completing the noncontact radiation survey and the visual inspection, the robot returns to its starting position and awaits the next step. This allows the operator to visually verify that the robot has completed the task.

When the noncontact surveys are complete, the RRSAS performs a contact swipe survey at multiple points (currently 40) on the cask surface, then analyzes the radiation emanating from the contaminated swipes. As shown in Figure 3-6, the swipes consist of filter paper mounted on semicircular plastic plates that are flat on one side. A 3/16-in.-thick piece of foam rubber between the filter paper and the plastic plate provides the passive compliance needed for active force control of the robot during the swiping process (see Section 2.5). Swipes are individually dispensed from a supply magazine (Figure 3-7, and Appendix D) mounted on the robot structure. The robot uses its gripper to pick up a swipe (Figure 3-7) and then proceeds to a cask swipe point.

Swipe points on the cask surface are randomly generated by the supervisory computer using the CAD model of the cask. Computer graphic displays are used to show the operator which point will be swiped (Figure 3-8). The operator can then visually verify that the robot is moving to the proper location. The computer automatically programs the robot arm movements, or trajectories, through space to prevent collisions with cask features such as the lifting trunnions. The computer also automatically positions the swipe normal to the surface being surveyed and determines the proper direction to move during the swiping process. For example, during swiping of the top of the simulated lifting trunnion, the computer directs the robot to approach the trunnion in a manner that avoids collision with the impact limiter (Figure 3-9). The swipe is automatically oriented so that the flat edge (Figure 3-6) fits into the joint formed by the square lug and the cask body. Finally, the computer directs the robot to move to the right during the swiping process, avoiding collision with the impact limiter.

The RRSAS swiping process is performed using force control. The system uses a commercial force sensor mounted near the end of the robot arm (Figure 3-8). During a swiping operation, the robot approaches the cask's surface to within 1 in. under position control and then makes contact with the cask under force control.

Position control, under which the RRSAS robot is commanded to move to positions in space, is the normal operational mode for most commercial robots. This type of control is inadequate for making contact with the cask's surface, due to small inaccuracies in the RRSAS. If, for example, the RRSAS robot is commanded to move to a position believed to be on the cask's surface, and it is, in fact, 0.01 in. above the surface, swiping cannot be accomplished, since the swipe is not touching the surface. Because of this, force control, which is used when the RRSAS robot is commanded to press with a specified force on the cask's surface, was developed by SNL for the RRSAS project (see Appendix A).

Once contact has been made, robot control is partitioned. Force control provides for movement normal to the cask's surface to maintain a desired contact force, i.e., stiffness control, and position control provides for

Figure 3-6. Contact Contamination Swipe Fixture

Figure 3-7. Robot Retrieving a Swipe From the Supply Magazine

Figure 3-8. Computer Display of a Randomly Generated Swipe Location

Figure 3-9. Robot Swiping the Top of the Lug

movement along the cask body. This type of dual hybrid force/position control allows swiping of the cask surface while maintaining a constant contact force. As shown in Figure 3-10, the initial contact force of 7 to 8 lb is reduced to 4 lb within 1/2 s, and the robot maintains this reduced force (± 1 lb) during the 4-s swipe. Extensive development at SNL in hybrid force/position control technology, together with robot-controller modification, have been required to allow the 4,500-lb robot to achieve this precise level of control.

When a swiping process is complete, the used swipe is placed in a storage magazine. Upon completion of the entire contact swipe survey, the robot picks up the storage magazine and delivers it to a Canberra swipe reader (Figure 3-11). This reader was modified by SNL engineers to provide for computer control and automatic swipe feeding. Once the magazine is delivered to the reader, it is locked into place, and the reading process begins.

Contact survey results are displayed to the operator on a computer terminal. The operator is alerted to all contamination survey results higher than predetermined specifications. Contaminated locations, should they occur, are indicated by a blinking light on the graphic display of the cask. All high-radiation readings are associated with the sample location on the cask surface, and provisions are made for automatically returning the robot to that location for resurvey, if desired. The time required to accomplish the radiation and contamination survey test for 40 randomly generated swipe locations is approximately 29 min. Manual surveys typically require approximately 120 min to perform all swiping, detector, counting, and analysis operations (Schneider et al., 1987). Further systems analysis indicates that this total swiping time could be reduced by 25 to 50 percent by reducing electronic delays within the robot controller, thus allowing the robot to operate safely at higher speeds.

3.4 RRSAS Control Concept

The RRSAS supervisory control system is the integrating agent for the entire robotic system. Robot system control may be either manual or automatic. Manual control is used for error recovery situations when the operator must move the robot under teach pendant control. The gantry robot teach pendant is shown in Figure 3-12. The operator commands the robot to move by pushing the appropriate buttons on the teach pendant. When using the teach pendant, the operator must provide all the detailed robot motion commands required to accomplish a given robot task.

Under programmed control, the operator serves in a supervisory capacity only, verifying that the system is operating correctly. The RRSAS supervisory control environment supports both computer reasoning about robot actions, such as planning of collision-free robot movements, as well as sensor-based control, e.g., force control. In addition, supervisory control provides for recovery from error situations and integrates the diverse RRSAS subsystems with a reliable functioning system (see Appendix C).

The structure chosen for the control system is shown in Figure 3-13. This structure is similar to that of many human organizations in which a supervisor controls the activities of several subordinates with specialized

Figure 3-10. Forces During In-Contact Swipe Operation

Figure 3-11. Robotic Delivery of the Swipe Canister to the Reader

Figure 3-12. The Gantry Robot Teach Pendant

Figure 3-13. The RRSAS Control System

abilities. In such an organization, the supervisor tells the subordinates what needs to be done and when, but does not issue detailed instructions on how to perform a task; the subordinates have special knowledge on how to perform the tasks for which they are responsible. In addition to giving task instructions, the supervisor also coordinates the subordinates' activities to achieve a desired objective. The RRSAS controller functions in a similar fashion.

A Sun Microsystems model 3/160 computer serves as the supervisory computer. This computer monitors and schedules the activities of six subsystem controllers; the swipe reader, robot, real-time force control for swiping, vision, bar code reader, and noncontact radiation scanner. In addition, the supervisory computer provides an operator interface that includes high-speed graphics display. This display, as discussed above, serves two primary functions. First, the radiation survey results are displayed to the system operator to allow him or her to determine whether resurveys are needed. Next, during the random swipe process, graphics are used to show the operator the swipe point location, so that robot movements can be monitored. Although the RRSAS has proven to be extremely reliable, safe operation procedures dictate operator verification that the robot is indeed moving to the correct location on the cask.

The supervisor combines data from the computer vision subsystem with the mathematical description of the cask, or CAD description, to build a model of the robot and cask world. This model consists of the robot's location as well as the cask's location with respect to the robot. Procedures for executing specific tasks are also integrated with this model of the robot world. The required tasks, e.g., swiping the cask surface, are analyzed within the context of the model to develop commands that must be communicated to individual subsystem controllers, such as the swipe controller, for execution. Each subsystem controller is responsible for executing the supervisory commands and returning messages that indicate successful or unsuccessful completion of the command, plus any required data resulting from command execution, as in the vision system.

The primary reason for adopting the control architecture shown in Figure 3-13 is to allow control distribution throughout the system to support the requirements for different types of control, facilitating real-time sensor-based control and model-based high-level control. This control architecture is similar to methods used in human organizations to provide efficient use of subordinates' skills. The RRSAS is comprised of many specialized subsystems. The structure represented in Figure 3-13 allows the use of multiple computing environments, adapted to the particular needs of each task, e.g., vision, and all coordinated by a single supervisor. Details of the supervisory control are presented in Appendix C.

In addition, the control architecture in Figure 3-13 provides a structure within which to construct the required system control algorithms in a modular fashion. Software development is based on a modular building-block approach with single-page, single-purpose routines building on one another to produce a complex control structure reflecting the cask processing requirements.

3.5 Swing-Free, Oscillation-Damped Transport

During the development of the RRSAS project, personnel associated with repository design efforts became concerned with the significant processing times predicted for heavy material movement using standard bridge crane technologies. The RRSAS provides an excellent experimental environment for examining alternative material movement strategies. Earlier work at SNL suggested the feasibility of transporting objects suspended by a cable without developing significant pendulum motion. The gantry robot in the RRSAS has been used to simulate a computer-controlled bridge crane. Gantry acceleration is controlled using a mathematical model of a pendulum. Proper acceleration control of the gantry bridge allows damping of any residual swinging of suspended objects in one swing period. This results in significant decreases in material transport times (see Appendix E).

The approach adopted to move objects without residual swinging is shown in Figure 3-14. While suspended from a bridge crane, an object such as a spent fuel assembly that is initially at rest, will begin to swing if the bridge crane moves. The motion of the object will be similar to that of a simple pendulum. To move these objects without residual swinging, SNL uses the characteristics of pendulum motion in its approach.

Consider an object swinging like a pendulum about a fixed point. At the two extremes of its swing, the object must stop momentarily to change direction. Now consider Figure 3-14, where the point about which the object swings is continuously moving. Note that in Figure 3-14 the object suspended from the bridge crane continues to move at the two extremes of its swing. However, the object's motion with respect to the bridge crane stops for its direction of motion to change. Therefore, at the two extremes of its swing, the object suspended from the bridge crane in Figure 3-14 momentarily moves at exactly the same velocity as the bridge crane.

If the acceleration of the bridge crane is constant, as in the constant bridge acceleration example in Figure 3-14, the two positions where the swinging object will come to rest are somewhere to the left of and directly beneath the moving bridge crane. Oscillation is the point at which the swinging object returns to a point directly beneath the moving bridge crane. If, after one period of oscillation, the bridge crane acceleration is instantly set equal to zero, the object will no longer swing as the crane continues to move, because the crane and the object now have exactly the same velocity. The net result, as in the constant velocity of bridge and object example in Figure 3-14, is that the object travels directly beneath the bridge crane without swinging.

As shown in the bridge- and object-at-rest example in Figure 3-14, the bridge crane can be brought to a complete stop with zero resultant swing of the object. Here, a constant rate of deceleration for the bridge crane is selected. The rate of deceleration is selected so that the bridge crane comes to a rest after exactly one period of suspended object oscillation. As the crane slows, the object swings out in front of the moving crane. As discussed above, however, if the rate of deceleration is constant, the swinging object will return to a point directly beneath the crane after one oscillation period. At that time, the object's velocity will be equal to the

Figure 3-14. Oscillation-Damped Motion

bridge crane's velocity. Thus, if the deceleration rate was selected so that the bridge crane's velocity was exactly zero after one period, the object's velocity would also be zero; the object would be stopped without swinging.

3.6 Summary

Robotic execution of nuclear waste shipping cask radiation and contamination surveys offers potential for significantly reducing personnel exposure to radiation. Technology developed during the RRSAS project demonstrates that large, heavy robotic systems can operate under real-time force control to perform contact swipe surveys. This technology not only allows health-physics surveys of nuclear waste shipping casks to be done remotely, but provides enhanced repeatability of the process. Automated data collection and analysis provide improved evaluation of the survey results and automatically generate archival data for tracking cask histories and quality assurance purposes.

The RRSAS project was successfully completed in August 1987 and is currently operational. The computer vision system can locate a shipping cask with an accuracy of 1.5 mm (0.06 in.) in two dimensions and 2.5 mm (0.10 in.) in range. This is better than the gantry robot's worst-case measured accuracy of 0.56 cm (0.22 in.). Thus, the robot's accuracy dominates the safe approach distance of the robot to the cask surface.

Hybrid force/position control, described in Section 3.3, allows swiping of the cask surface with 4 lb of force, ± 1 lb. This force is maintained during the swipe process. The entire swipe process from moment of contact to end of swipe requires 5 s.

Operational times for completing all RRSAS tasks under programmed operation by the supervisory computer are shown in Table 3-1. The time for reading the swipes is indicated as variable because each swipe is measured for a length of time sufficient for proper counting statistics. Thus, the time of counting is a function of the contamination level. Recent experiments in which the effect of electronic delays within the force control system have been reduced show that total swiping time can be further reduced by approximately 25 to 50 percent.

Oscillation-damped movement of objects using a computer-controlled bridge crane, as simulated by the XR[®] 6100 gantry robot, is feasible. Tests with the RRSAS robot have shown that a simply suspended object can be transported approximately 15 ft in 2 s with a residual oscillation of less than 0.1 degrees. Such movements not only greatly reduce the time for material transport, but also allow for obstacle avoidance because the suspended payload is not swinging.

The RRSAS project has identified many cask design features that significantly impact the feasibility of robotic cask handling, e.g., clearances for overhead approach, high-contrast unique visual reference points, and provisions for lifting points directly over the object's center of gravity to allow swing-free transport (Griesmeyer and Thunborg, 1988). Of particular importance are cask designs that can be efficiently represented and modeled by a computer. The RRSAS is strongly model-driven because it must operate in an unstructured environment, select random cask swipe locations, and

Table 3-1
RRSAS Operation Times

Process	Time Required (min)	
System Initialization	1.10	
Visual Location of Cask	1.25	
Read Bar Code	1.00	
Radiation Survey (Beta/Gamma)	2.60	On-Line Operations
β, γ Data Processing/Display	0.75	
Take Contamination Swipes (40)	23.40	
Load Swipe Reader	0.75	
Total Radiation Survey Time	29.75	
Read Swipes and Display Results	Off-Line Operation of Variable Duration	

determine the appropriate robot movement for executing swiping operations based on a CAD model of the cask. In addition, the RRSAS must efficiently respond to sensor inputs, not only to directly control robot movements such as force-controlled swiping, but to detect and respond to error situations. Cask designs based on simple geometric shapes greatly simplify computer modeling and the model used for controlling robot actions. In addition, design symmetry greatly facilitates both modeling and subsequent reasoning processes.

4.0 CONCLUSIONS

4.1 Technical Achievements

The RRSAS was successfully completed in August 1987 and is currently **operational**. Over 200 demonstrations have been performed since that date. The RRSAS achieves fairly high reliability (for a laboratory system) by using models of the robot and its environment to automatically program the needed robot trajectories without human intervention. This significantly reduces the potential for human error. In addition, should an error occur, the model-based controller can frequently recognize the error situation and recover automatically. Integration of such error recovery strategies into the knowledge base of the robotic system significantly increases the system success. A common error, for example, is misinterpretation of shadows by the computer vision system for visual reference features during the cask location operation. However, since the computer model directing the robot incorporates knowledge of the visual reference features, an error is typically detected and the robot system automatically reevaluates the visual reference feature from a slightly different vantage point to overcome the effects of the shadows. Automatic programming of robot trajectories from models also allows swiping of randomly selected locations on the cask's surface. Without automatic model-based programming of the robot's movements, swiping of randomly selected cask surface locations would not be possible.

The incorporation of force control into the robotic system allows controlled interactions of the robot with its environment, even in the presence of errors in the models. Force control is essentially a perturbation on the trajectories automatically determined from the models. Force control essentially corrects for slight differences between the real world and the models of the robot and its environment. High-speed force control allows contact swiping of the cask quicker than can be accomplished hands-on by an operator. The reliability of the swipe data is higher than manually achieved data because each swipe operation is identical to all other swipe processes.

Incorporation of computer vision into the RRSAS allows automatic location of objects, e.g., a nuclear waste shipping cask, within the workspace of the robot. This eliminates the need for expensive fixturing devices and allows a single robot system to deal with many different cask designs. Essentially, the computer vision system is used to update the model of the workspace environment which forms the basis for robot trajectories.

Finally, the model-based control philosophy incorporated in the RRSAS also allows swing-free transport of suspended objects, such as bridge crane transport of casks and cask components. In this case, models of object oscillatory behavior are used to determine acceleration profiles which transport simply suspended objects without residual oscillation. Such model-based control strategies greatly reduce the time required for materials transportation operations.

4.2 Feasibility of Using Integrated Robotic Systems for HLW Shipping Cask Operations

While the RRSAS project concentrates mainly on survey-type task performance, the successful integration of diverse components required to accomplish those tasks convincingly demonstrates that all perceived cask-handling operations can be accomplished using a total robotic system. In particular, the success of a model-based control approach in RRSAS operations provides a necessary alternative to both traditional remote-handling methods, based on master/slave manipulation, and man-in-the-loop automated concepts, based on repetitious teach operations. As noted previously, current commercially available robot control technology is restricted to repetitious movements among previously taught locations. Teaching, the most common mode of robot programming, involves manually moving the robot manipulator's end point to a location in the environment and storing that position in the robot's computer memory. With restricted personnel access to the robot workspace and the need to deal with off-normal conditions, this manual approach to robot programming is difficult. Thus, robot system control must be accomplished using a supervisory computer and models of the robot and its environment. Significant progress in model-based supervisory control has been demonstrated by the RRSAS.

4.3 Cask and Handling System Design Implications

Via RRSAS evaluations, Griesmeyer has thoroughly documented what has been determined to date regarding the impact of cask design features on robotic handling capabilities (Griesmeyer and Thunborg, 1988). Some of the major points are summarized here for completeness.

Critical to the success of model-based supervisory control is the computer model of the robot's world. This model allows the supervisory computer to interpret sensory data and automatically direct robot motions based on this sensory information. Simple cask geometries greatly facilitate task planning and supervisory control. Thus, cask designs should employ geometries that are as simple as possible, without compromising cask functionality. The RRSAS swipe operation depends on model-based control of a commercial robot and a single sensor (force). This technical approach, combined with a simple cask geometry, has allowed the RRSAS to perform a wide range of contact-based manipulation tasks not previously demonstrated such as mechanical assembly and radiological swiping. In fact, the radiological swiping operations can likely be performed faster robotically than manually. Simplified cask geometry will also allow easier manual swipe operations.

Given the restrictive capabilities of currently available robotic systems, design of the robot's work environment is extremely important to the success of applying robotic systems to remote-handling tasks. Experience with the RRSAS indicates that modest design changes that do not change the functionality of major cask components can significantly affect the ability to robotically execute various cask operations. Symmetries and alignment tapers for self-guiding assembly, which reduce requirements both for accurate alignment of components and the complexity of robot control algorithms, can reduce the time for such robotic operations by up to two orders of magnitude over designs without these features.

Other limitations of current robotic systems exist but are expected to be overcome in the near future. While not yet commercially available, sensor-based controls exist. Force-control capabilities have been demonstrated with the RRSAS, but the vision system is still limited to location tasks only (i.e., vision servo control has not been demonstrated).

Limited degrees of freedom and the need for special end effectors, or tools to perform various tasks, require that clearances be provided on a cask for the approach of the often bulky end effector and changer mechanism. Straight-line approaches should be used. The expense of robotic systems provides incentive to employ only one multifunction robot in a given workspace. Overhead gantry robots are likely candidates and, thus, clearances for straight-line overhead approaches are desirable.

Other design features could limit RRSAS survey operations. Obstructions could interfere with radiation and visual scans of the cask and transporter exterior surfaces. Uneven surfaces and recesses are difficult to access in a robotic swiping operation. All component surfaces should be comprised of simple, mathematically definable shapes.

Many more specific cask design implications based on RRSAS experience with other operations are summarized by Griesmeyer and Thunborg (1988). Griesmeyer and Thunborg concluded that cask interface design and operational features can be defined to facilitate robotic cask handling with minimal impact on a cask's functional requirements.

4.4 Transportation System Impacts

Operations with the RRSAS clearly illustrate that robotic handling of nuclear waste shipping casks at receiving facilities will significantly reduce occupational exposures. The experience gained from the development and operation of the system has been used to evaluate an automated handling system alternative to the postulated reference system of the ALARA analysis (Schneider et al., 1987). Conceptual details of the system have been developed by a team of SNL and Westinghouse Hanford Company personnel based on both RRSAS operations and earlier proof-of-principle experience (Berger et al., 1986). Two cases have been considered: a totally remote system and a partially remote system; neither optimized for remote operations.

The resulting integrated dose to cask-handling workers at a repository has been estimated to be reduced from 418 person-rem/yr for the postulated reference system to 5 person-rem/yr for the totally remote automated system. With an estimated total crew of 80 people, the average dose to individual workers in the totally remote system would be approximately 60 person-mrem/yr, well within ALARA guidelines.

Estimates of the operational times for this alternative have indicated that remote operations should not take longer than manual operations. In the ALARA comparison, the operational and turnaround times for the automated-handling concept are estimated to be equal to the postulated reference case. More recent experience with the RRSAS indicates that the time estimates used in the ALARA analysis for swipe surveys and moving large objects could be further reduced with a corresponding reduction in turnaround times. Changes

in operational times of the remote automated alternative, however, would only slightly impact the dose to workers since workers would not be near the casks, but rather would be located in control rooms with low background dose rates. Therefore, operational times for alternative remote automated-handling concepts are not of major importance to doses received by workers. However, changes in operational times could have important effects on system costs. Regardless of time considerations, the automated concept has been found to be the only alternative that could decrease the annual doses to repository workers to the level desired by DOE design objectives.

The costs of using robotics in the repository cask-handling system have also been estimated for the ALARA analysis (Schneider et al., 1987). The capital cost for the totally remote system is estimated to be nearly \$19 million (1987). Using a totally remote automated system at the receiving and handling facility would result in an estimated staff reduction of 31 persons by reducing requirements for operators, maintenance-craftsmen, quality control persons, crane operators, and radiation monitors. Reducing the repository labor force by the above amount would result in an estimated labor cost decrease of \$1.3 million per year.

As noted, the original handling times estimated for the advanced remote concept of the ALARA analysis are of the same range as the postulated manual operational reference case. Optimization of the facility for robotic operations would reduce those times considerably (Yount and Berger, 1984). Also, more recent RRSAS experience indicates the time required for many cask operations could be reduced by another factor of two or more below that required for manual operations. This could result in a reduction in the number of handling bays at a repository, as well as a possible reduction in the number of individual casks in the system due to the reduced turnaround time requirements. Thus, a fully optimized robotic system could achieve a benefit-benefit situation; dose reduction with cost savings.

As noted, minor design modifications significantly impact the feasibility of robotic cask handling. The design process becomes one of attention to detail rather than radical alteration of concepts (Griesmeyer and Thunborg, 1988). Handling simplicity also results in designs more easily handled during manual operations, and thus lower exposures at repository facilities.

Operations reliability and quality are also significantly improved since all procedures are conducted in a prescriptive, software-directed manner. Quality assurance is provided by a continuously updated data base that determines when an operation is completed by comparing feedback data to limits. This improved quality will result in significant reductions in error probabilities commonly dominated by human error rates on the order of 10^{-3} to 10^{-5} per task (Sanders et al., 1987).

In summary, experience gained from the development and operation of the RRSAS provides proof of the technical feasibility of a fully robotic cask-handling concept. Little design impact on transport casks is required for most operations. Exposure levels of repository operations can be reduced significantly with improvements in processing rates, task reliability, quality and verifiability, and general occupational safety. These benefits could occur with cost savings, resulting in a benefit-benefit situation.

REFERENCES

- Berger, J. D., B. C. Gneiting, and T. L. Sanders, 1986. "Use of Robotics for Radioactive Waste Shipping and Receiving," *Proceedings, PATRAM'86*, Davos, Switzerland, 2:485.
- DOE (U.S. Department of Energy), 1981. "Requirements for Radiation," Order 5480:1A, Washington, D.C., Chapter 11.
- DOE (U.S. Department of Energy), 1986. "Development of From-Reactor Casks," DE-RP07-861D12625, Idaho Operations Office, Idaho Falls, ID.
- Griesmeyer, J. M., and S. Thunborg, 1988. "Remote Cask Handling and Implications for Cask System Design," SAND87-2670, Sandia National Laboratories, Albuquerque, NM.
- Madsen, M. M., W. L. Uncapher, D. R. Stenberg, and E. E. Baynes, 1987. "Testing the Half-Scale Model of the Defense High-Level Waste Transportation Cask," SAND86-1130, Sandia National Laboratories, Albuquerque, NM.
- NWPA, The Nuclear Waste Policy Act of 1982, as signed by the President on January 7, 1983 (Public Law 97-425, 96 Stat. 2201, 42, U.S.C. 10101).
- Sanders, T. L., R. M. Westfall, and R. H. Jones, 1987. "Feasibility and Incentives for the Consideration of Spent Fuel Operating Histories in the Criticality Analysis of Spent Fuel Shipping Casks," SAND87-0151, TTC-0713, Sandia National Laboratories, Albuquerque, NM.
- Schneider, K. J., W. A. Ross, R. I. Smith, P. M. Daling, R. B. Grinde, C. J. Hostick, R. W. Peterson, D. L. Stiles, S. A. Weakley, and J. R. Young, 1987. "Analysis of Radiation Doses from Operation of Postulated Commercial Spent Fuel Transportation Systems," DOE-CH/TPO-001, Pacific Northwest Laboratory, Richland, WA.
- Shirley, C. G., 1983. "NWTs Transportation Interface Technology Development Priority Report," SAND82-1804, TTC-0336, Sandia National Laboratories, Albuquerque, NM.
- Strip, D. R., 1987. "Robotic Handling of Spent Fuel Shipping Casks: Preliminary Assessment of Cask Design Impacts and Technology Development Needs," SAND86-2470, Sandia National Laboratories, Albuquerque, NM.
- Winson, G. H., et al., 1980. "Opportunities to Increase the Productivity of Spent Fuel Shipping Casks in the United States," PNL-3017, TTC-0078, Pacific Northwest Laboratory, Richland, WA.
- Yount, J. A., and J. D. Berger, 1984. "Conceptual Design Report for a Remotely Operating Cask Handling System," HEDL-7376, TTC-0449, Rev. 1, Hanford Engineering and Development Laboratory, Richland, WA.
- Zimmer, A., and M. M. Madsen, 1985. "A Defense High-Level Waste Shipping Cask Design," *Proceedings, Waste Management 85*, Tucson, AZ, 3:337.

APPENDIX A

FORCE SERVO CONTROL OF A COMMERCIAL GANTRY ROBOT*

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ABSTRACT

Sandia National Laboratories is investigating robotic handling of spent nuclear fuel shipping casks for proposed geologic waste repositories. Robotic handling will impact not only transportation cask design, but also the overall design of the waste repository. A goal of robotic handling is the reduction of personnel radiation exposure. One of the major technology development areas has been the integration of sensors into the robot control system to allow operation in semistructured environments. In particular, a multiaxis force sensor is used to make robot trajectory corrections based on the contact forces between the robot and cask. This force feedback system allows contact swipes (smears) to be made on the cask surface in a safe, repeatable manner.

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INTRODUCTION

As part of a project to investigate the impact of robotic handling on the design of nuclear waste shipping casks, Sandia National Laboratories (SNL) is developing a force-controlled robotic system to perform radiation surveys of nuclear waste shipping casks (Thunborg, 1987). This appendix discusses the approach to the force-control problem and implementation of a force-controlled robotic system. The approach to force control includes not only theoretical considerations, such as control algorithms and control space partitioning, but also semiempirical considerations, such as system compliance and servo gain determination. Finally, results obtained with the initial and improved implemented robotic system at SNL are reviewed.

Recent work has demonstrated that force feedback can allow a commercial robot to work in semistructured environments (Starr, 1986; Thunborg, 1986; Petterson and Jones, 1987). The objectives of the work described here are to determine if robotic radiation and contamination surveys of nuclear waste shipping casks in semistructured environments are feasible, and to evaluate the impact of robotic handling on the design of these shipping casks. Robotic execution of cask surveys offers distinct advantages over manual execution of these tasks. These advantages include reduced human radiation exposure (DOT, 1984), high repeatability of radiation survey procedures (Westinghouse Hanford Company, 1986), and accurate correlation of radiation survey data with sample locations on the cask surface. In short, for a robotic survey to be feasible, the robot must accurately collect data while maintaining safe, reliable operation, and must produce process flows consistent with the desired facility throughputs.

APPROACH TO FORCE CONTROL

Commercial robots typically provide only position control and no force control. Thus, an existing robot controller must either be replaced or modified to provide force control for a commercial robot. SNL's approach was to modify a CIMCORP XR®* 6100 gantry robot controller to provide hybrid force/position control by developing a force-control loop around the position-control loop of the existing controller.

The position-control servo loop used in the XR® 6100 controller is shown in Figure A-1. The servo loop consists of a proportional/differential controller where the position error, X_e , is used to generate the error signal that drives the robot arm to the desired position, X_d (Craig, 1986). The robot's velocity, $\dot{X}$, is monitored to provide damping for stable operation. As with most commercial robots, the control system for the XR® 6100 controller is significantly overdamped to prevent position overshoot.

Figure A-2 shows the force-control strategy developed for this work. The contact force between the robot and the workpiece is measured by a force transducer mounted between the wrist of the robot arm and the end effector. The contact force, F , and its derivative, $\dot{F}$, are the feedback parameters supplied to the proportional/differential force-control loop as shown. The force error F_e ($F_e = F - F_d$, where F_d is the desired contact force) generates

*XR® is a registered trademark of CIMCORP Inc.

Figure A-1. Position Control Servo Loop Used in the XR[®] 6100 Gantry Robot Controller

Figure A-2. Force Control Strategy

an error signal to drive the force error to zero. The rate of change of the contact force, $\dot{F}$, is used as a damping function. Sensed forces are typically noisy, and differentiation for control purposes is usually ill-advised (Craig, 1986). However, the slow response of the large electromechanical system used in this work effectively filters the force sensor noise.

Because the robot's position controller provides the driving signal to the robot, a position command must be generated by the force-control loop. Thus, the damped force error is multiplied by a stiffness matrix, S , which relates force to incremental displacement using the spring rate of the robot system (Salisbury, 1980). The resulting incremental displacement is communicated to the robot position controller and added to X_d to generate a new desired robot position. The robot's position controller then drives the robot to this new, desired position.

Due to the large spring rates (high stiffness) of most industrial robot manipulators, passive compliance must typically be added to the system to provide stable force control. The added compliance must be compatible with the robot's position-control characteristics. If the robot's finest resolution move results in large force variations due to excessive system stiffness, stable control will be difficult to achieve. However, if excessive compliance is added to the system, small changes in force will require large robot movements, making the system appear overdamped and unresponsive. Thus, the tradeoff is to reduce the robot system stiffness, which increases system damping, while maximizing system responsiveness to allow high-resolution force control. In addition, any compliance added to the robot system should be as close to the point of applied force as possible. Tools, or end effectors, mounted onto a compliant device may sag, inducing tool positioning errors.

Hybrid force/position control is accomplished by partitioning the robot's control space into force and position subspaces to simultaneously satisfy force and position constraints (Raibert and Craig, 1981). The strategy is to control selected robot degrees of freedom by force control, while using position control for others. In terms of Figure A-2, the stiffness matrix, S , is a diagonal matrix in robot tool coordinates, with zeros everywhere but the degrees of freedom under force control. Force-controlled robot trajectories are generated by summing the incremental position updates, X_1 , derived from the stiffness matrix, with the position commands defining the desired robot motion along the surface. This allows the robot to follow the contour of a surface while maintaining a prescribed force normal to the surface.

Finally, the control of any robot must be tuned to the characteristics of that particular robot. As discussed above, most commercial robot position controllers are significantly overdamped to eliminate position overshoot. However, force control is best implemented in a slightly underdamped position-control environment to provide fast response to changes in force. Thus, the values of k_p and k_v in Figure A-2 should vary depending on whether that particular degree of freedom is force or position controlled.

FORCE CONTROL IMPLEMENTATION

Hardware

The hybrid force-control system discussed above is implemented on a CIMCORP XR[®] 6100 robot at SNL. The XR[®] 6100 system consists of a 2,045-kg (4,500-lb) gantry manipulator and a digital six-axis robot controller. Force control using the XR[®] 6100 robot requires that three additional components be added to the standard robot: a force transducer, to monitor contact forces; a force-control computer, to perform force-control loop calculations; and a CIMCORP line tracker, to allow high-speed communication with the robot controller.

The force transducer is a JR3 force/torque sensor capable of converting forces along three orthogonal axes and the corresponding moments. The JR3 has an analog-to-digital converter and a microprocessor that convert the force and torque signals to digital readings and transmit the readings to the force-control computer.

The force-control computer is a Digital Equipment Corporation LSI-11/73[®] that executes the RT-11[®]* real-time operating system. As indicated in Figure A-2, the force-control computer monitors the force sensor, computes required position updates using the proportional/differential force-control algorithm, and communicates these updates to the line tracker. The line tracker provides the interrupt-driven communication for trajectory updates from the force-control computer to the robot position controller.

Compliance

In addition to the force sensor and computing hardware, passive compliance has been added to the robot arm. Experiments with the XR[®] 6100 robot arm have revealed spring rates of 53,000 to 120,000 N/m (300 to 700 lb/in.) depending on the arm configuration. The smallest commandable position change of the XR[®] 6100 is 0.025 mm (0.001 in.). This position change would result in a minimum change in force of 1.3 to 3.1 N (0.3 to 0.7 lb), depending on arm configuration. Because the goal of this arm modification is to control the applied force to within ± 4 N (± 1 lb) of the 18-N (4-lb) specified force during the swiping process, compliance is added to the robot system to improve system stability.

A 2.4-mm (3/32-in.) foam pad has been placed between the contact swipe and the robot end effector, reducing the effective spring rate to about 21,900 N/m (125 lb/in.). This decreased spring rate yields the desired force resolution while maintaining robot responsiveness.

Software

The force-control computer (Figure A-2) receives task information from a supervisory computer (Thunborg, 1987). This information includes controller gains (k_p , k_f), applied force magnitude (F_d) and direction, and lateral swipe distance and direction. The force-control algorithm is then implemented on

*LSI-11/73[®] and RT-11[®] are registered trademarks of Digital Equipment Corporation.

the LSI-11/73[®] computer as indicated in Figure A-2. In addition, the LSI-11/73[®] provides interrupt-driven communications to the robot position controller through the line tracker.

The JR3 force sensor communicates digital force data serially to the force-control computer. After the force-control computer receives a complete data set, the data are stored for use by the force-control algorithm.

Communication from the force controller to the robot position controller is through the line tracker. The line tracker issues a synchronizing pulse to the force-control computer every 47 ms. After receiving a pulse, the force-control computer transmits a position update to the line tracker and then computes the next robot position update using the proportional/differential force-control algorithm with the most recent force data set. After the next position update is calculated, the force-control computer waits for the synchronizing pulse from the line tracker before beginning the cycle again.

Synchronization and Timing

Force control must yield smooth, repeatable, and responsive motion of the robot arm to minimize force overshoots. Synchronizing the force-control routine with the update rate of the robot controller helps ensure smooth, repeatable, and responsive motion of the robot arm by allowing consistent experiments to accurately determine the force controller's parameters. In addition, the delay between changes in contact force and robot arm response must be minimized for responsive and stable force feedback control.

Reducing the delay between application of the force and the robot arm response is difficult because a large part of this delay occurs within the commercial hardware and software. In the initial implementation of force control on the XR[®] 6100 system, the time delay between force application and robot response is about 0.5 s. Approximately 0.22 s of this delay is due to the electronics between the force transducer and the robot servos (Table A-1), while about 0.28 s of the delay is due to the electromechanical system response.

Table A-1 shows the minimum delays found between the force transducer and the robot servos. Asynchronous operation of several of the components can introduce additional delays totaling 10 to 20 ms. The potential improvements listed in Table A-1 show the minimum delays obtainable without major system redesign for each component.

A significant delay results from a 16-Hz, fourth-order Butterworth filter used in the JR3 force amplifier (Step 1). The filter causes a phase shift in the force signal that delays the analog data by 40 ms. This delay can be reduced to 4 ms by using a 163-Hz filter supplied by JR3. Step 2, the analog-to-digital conversion of the force signal, takes 2 ms.

As initially set up, the JR3 samples the force signal every 10 ms (Step 3). This 10-ms delay can be reduced to 4 ms by requesting a faster sampling rate. But, because the JR3's force sampling runs asynchronously to

Table A-1

Electronic Delays Between Force Transducer and Robot Servos

Step	Shortest Delay		Component and Process Causing Delay
	Unmodified Equipment (ms)	Potential Delay (ms)	
1	40	4	(JR3) Butterworth Filter
2	2	2	(JR3) Force A/D
3	10	4	(JR3) Update Rate
4	20	0.5	(JR3) Buffer
5	11	5.5	(JR3) Serial Communication
6	0	0	(LSI) Data Age
7	3	3	(LSI) Calculations
8	43.875	10	(LSI) Synchronization
9	12	12	(LSI) Serial Communication
10	81.75	23.4375	(Traj) Internal Computations
Totals	223.625	64.4375	

the rest of the system, the actual delay due to force sampling could be twice that reported in Table A-1, if data were requested by the JR3 buffer just after the start of sampling, rather than just after sampling completion.

The data buffer in the JR3 produces a significant delay as well (Step 4). The JR3 has a first-in, first-out buffer that stores a minimum of 20 bytes of force information. At 9,600 baud, the time required for force data to pass through the buffer is 20 ms. Reducing the buffer size to 1 byte and increasing the baud rate to 19,200, reduces the buffer delay to 0.5 ms. Also, increasing the baud rate to 19,200 reduces the time required to transmit one force data set (11 bytes) to the force control computer from 11 to 5.5 ms (Step 5).

Step 6 indicates that the force-control computer will always use data that is zero ms old; however, zero ms is a minimum delay. If the force computer begins its calculations before it receives a complete data set from the force sensor, the computer will use the previous data set received from the sensor. Depending on when the force computer begins its computations during the force data set transmission, the force computer may be using data that is up to 11 ms old (5.5 ms in the improved case).

Computation of a position update using the force-control algorithm on the force-control computer takes 3 ms (Step 7). However, a 44-ms delay is introduced while the force computer waits for the synchronizing pulse from the line tracker to begin transmitting the position update (Step 8). With a better synchronization scheme between the force computer and the line tracker, the 44-ms delay could be reduced to an estimated 10 ms. Finally,

the serial communication of the position update to the line tracker takes an average of approximately 12 ms (Step 9).

Once the line tracker receives the position update, the robot position controller takes approximately 82 ms to compute the appropriate motor drive signals (Step 10). CIMCORP is investigating changes to their controller that could reduce this delay to approximately 24 ms.

In addition to the improvements in digital implementation, increasing the servo gain (Figure A-1) reduces the time constant of the electro-mechanical system by approximately 60 ms. Also, the JR3 offers a parallel communications option that could potentially eliminate nearly all delays associated with Steps 4, 5, and 6. Ultimately, CIMCORP may be able to synchronize all processes in Step 10 to eliminate approximately an additional 12 ms.

RESULTS AND DISCUSSION

Figure A-3 shows the forces developed during a typical swiping operation. The goal is to move 10 cm (4 in.) along the cask surface while maintaining 18 ± 4 N (4 ± 1 lb) normal contact force.

The solid line in Figure A-3 shows the forces generated using the initial implementation (see the Synchronization and Timing Section). The maximum applied force is 39 N (8.8 lb). Stable force control is established after approximately 1 s, after which the hybrid controller executes the required robot lateral movement to generate the swipe trajectory while maintaining the specified normal force. From time of initial contact, total swipe execution requires approximately 5 s.

Figure A-3 also displays system compliance characteristics. Immediately after contact (zero s), the force curve shows significant curvature due to the compliance of the foam pad in the swipe tool. As the applied force increases beyond 18 N (4 lb), the slope of the force curve steepens significantly due to compaction of the foam pad. This increase in the force curve slope represents transition of system compliance from the foam pad to the robot arm. Notice that the added system compliance provides near-optimum compliance for force control at the 18-N (4-lb) level.

To improve the response of the system, the position controller gain, k_p , in Figure A-1 can be increased in the CIMCORP controller. Also, to quickly achieve the desired contact force with minimum force overshoot, a semi-empirical strategy for damping robot motion, termed jumpback, is implemented. Due to the overdamped nature of the robot position controller, the robot requires approximately 1 s to complete a move on the order of 1 to 100 mm. Thus, if immediately after contact the robot is commanded to stop, the robot remains in motion for a full second until the last commanded move is fully executed. To cancel this residual robot movement, the robot is issued a new position command 1.5 mm, or approximately half the thickness of the foam pad, back from the previously commanded position. This new position goal creates a smaller position error, X_e , in Figure A-2, which slows the arm's movement. The force controller then servo controls the robot to the desired contact force.

Figure A-3. Forces During Swipe Operation

Robot controller delays can also be observed at the start of the swipe trajectory. Although the command to initiate lateral robot movement is issued by the hybrid controller approximately 0.75 s after initial contact, lateral movement does not actually begin until approximately 0.28 s later.

The dotted curve in Figure A-3 shows an improved force-control implementation. By reducing the controller delays associated with Steps 1 through 5, as shown in Table A-1, the force overshoot is reduced to 31 N (7.1 lb) and stable force control is established sooner. Therefore, if the remainder of the delays could be reduced, as noted in Table A-1, it is reasonable to assume that further improvement could be obtained.

CONCLUSIONS

Hybrid force/position control can be implemented using commercially available robot controllers through the addition of a force-control loop around the existing position-control loop. The addition of hybrid force/position control greatly increases the utility of commercial robots by allowing them to make controlled contact with objects in their environment, and to perform force-directed manipulations, such as swiping the cask surface. It is possible to perform contact swipe operations consistently maintaining 18 ± 4 N (4 ± 1 lb) using a standard robot arm weighing 2,045 kg (4,500 lb) by employing the hybrid force/position technology developed in this project.

For a given mechanical system, the hybrid force/position controller response is directly related to the responsiveness of the system electronics. Currently, commercially available equipment can cause long delays, from the time initial contact occurs to the time the robot arm begins to react to the contact. These delays are typically due to large buffer sizes in asynchronous communications, asynchronous component operation, slow update rates of synchronous components, and overdamped position control of commercial robot systems. By reducing these delays, improved performance of force-directed tasks is obtainable. SNL is working with CIMCORP and JR3 to develop more responsive systems to allow more effective force control.

Robotic contact contamination surveys are feasible, and the time it takes to execute such surveys appears to be competitive with human performance. In addition, superior data collection, storage, reduction and presentation, and correlation between radiation survey data and sample location on the cask surface can be obtained using computer-based systems.

Hybrid force/position control partitions the robot control space into force- and position-control subspaces. This requires knowledge of the cask geometry for efficient control, particularly with overdamped robotic systems. If the surface geometry is not well known, and the commanded tangential move results in either breaking contact with the surface or pushing the robot strongly into the cask surface, the force-control subsystem will create large variations in applied force. The net result will be inconsistent force application during the swiping process and a much slower swiping process. Thus, smooth, well-defined surfaces that lend themselves easily to computer modeling greatly facilitate force-controlled robotic processes.

REFERENCES

Craig, J. J., 1986. *Introduction to Robotics Mechanics and Control*, Reading, MA: Addison-Wesley, pp. 223-252.

DOT (U.S. Department of Transportation), 1984. "Hazardous Materials Regulations," rev. ed., 49 CFR 100-177, Sec. 173.442.

Petterson, B. J. and J. F. Jones, 1987. "Force Control of a Robot for Surface Contamination Detection," *Remote Systems Technology Division Proceedings*, American Nuclear Society Winter Meeting, pp. 140-143.

Ralbert, M. H. and J. J. Craig, 1981. "Hybrid Position/Force Control of Manipulators, *Transactions of the ASME*, 102:126-133.

Salisbury, K. J., 1980. "Active Stiffness Control of a Manipulator in Cartesian Coordinates," paper presented at the 19th IEEE Conference on Decision and Control, pp. 1-6.

Starr, G. P., 1986. "Edge-Following with a PUMA 560 Manipulator Using VAL-II," *Proceedings of the 1986 IEEE of the International Conference on Robotics and Automation*, 1:399-383.

Thunborg, S., 1987. "A Robotic Radiation Survey and Analysis System," *Remote Systems Technology Division Proceedings*, American Nuclear Society Winter Meeting, pp. 133-139.

Thunborg, S., 1986. "A Robotic System for Remote Maintenance of a Pulsed Nuclear Reactor," *Proceedings, 34th Conference on Remote Systems Technology*, pp. 181-186.

Westinghouse Hanford Co., 1986. "Preliminary Design Report for a Remotely Operated Cask Handling System," Hanford, WA.

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APPENDIX B

COMPUTER VISION FOR SHIPPING CASK LOCATION

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ABSTRACT

This appendix discusses a robot vision system developed to locate shipping casks. The system uses arm-mounted stereo cameras for close-up views of handling lugs, or trunnions, on the cask, enabling location of an 8-ft-long cask model to within 0.2 in. The system operates with ambient light, accommodating wide variations. It also detects and attempts to recover from error conditions.

INTRODUCTION

The Remote Radiation Survey and Analysis System (RRSAS) project at Sandia National Laboratories (SNL) is intended to examine the impact of robotic handling on nuclear waste shipping cask design (Thunborg, 1988). Since the casks would be delivered by truck or rail and since they are quite massive (20 to 125 tons), it is not feasible to position them with great accuracy at delivery. The robot vision system described in this appendix determines the position of a prototype shipping cask to within 0.2 in., allowing subsequent robotic handling. The cask model is roughly cylindrical and measures approximately 8 ft long and 30 in. in diameter, approximately one-half the size of a full-scale truck shipping container.

TASK DESCRIPTION

The robot used for cask operations is a CIMCORP XR®* 6100 six-degree-of-freedom gantry robot (Figure B-1). The cask location is specified by determining the three-dimensional position in the robot's base coordinate system of each of three handling lugs or simulated trunnions on the cask. Since the lugs are not colinear, their locations uniquely define the cask position. To make the lugs readily identifiable, they have been painted flat black for high contrast with the white exterior of the container. The center of each lug is to be located within 0.25 in.; location accuracy should not degrade for full-scale containers. It is assumed that the vehicle carrying the cask has been parked within 18 in. of a specified nominal position. Skylights in the demonstration facility result in wide variation in the ambient lighting; the vision system should accommodate this variation as much as possible to minimize special lighting requirements. Based on the required throughput, approximately 2 min are available for the location operation.

RRSAS VISION SYSTEM

The RRSAS vision system uses two Sony XC-37 charge-coupled-device (CCD) RS-170 video cameras mounted on the robot arm at a position allowing four degrees of freedom: three degrees of translation and one degree of rotation. The camera resolution is 384 pixels horizontal and 480 pixels vertical. The cameras are mounted for stereo viewing, with a baseline of 24 in. This configuration allows close-up views of lugs and rotation to view lugs on both sides of the cask. The rotation also allows a particular lug to be viewed from many positions.

Using cameras mounted in fixed positions, rather than on the robot, has also been considered. If such cameras viewed the entire workspace, better than half-pixel accuracy would be required for the lug location in the image, and the lugs would be only about 8 pixels across--an undesirably small target. In addition, the larger field of view required for full-scale casks would have reduced location accuracy. Alternatively, fixed cameras could have viewed the smaller area of interest, the area where the lug is expected to appear, using one pair of cameras for each lug. This would have given a similar field of view to that presently in use.

*XR® is a registered trademark of CIMCORP Inc.

Figure B-1. RRSAS System Robot and Cask

However, the arm-mounted cameras are preferred due to their greater flexibility. The arm-mount position enables easier view position selection and facilitates modifications, such as locating additional lugs or averaging multiple-lug views. In addition, the movable cameras more readily support future vision tasks. The ability to change view positions is useful in the error recovery procedure.

Another configuration considered has been a single, arm-mounted camera moved by the robot for stereo views. This configuration has been rejected because robot position errors would not simply add an offset to the measured lug position, but would affect the stereo baseline, leading to much larger errors.

SYSTEM DESCRIPTION

Figure B-2 shows an overview of the vision system. The RRSAS vision process requires coordinated activity by the robot and an image-processing subsystem in response to commands from the RRSAS supervisory program. The main vision program runs on the host computer, a Sun Microsystems 3/160. This program, the vision server, provides computer vision services for the RRSAS supervisory program, or the client. The server accepts commands from the client and directs the image-processing computer and robot operations. The vision server can control the position of the robot with requests to the RRSAS supervisory program. Image-processing operations are performed by a Machine Vision, Inc. Genesis 4000 computer vision system (MVI, 1986). This unit, called an Image Flow Computer (IFC), serves as a vision peripheral to the host computer; communication is via RS-232 lines. The IFC is programmable in the C language, so, in principle, any algorithms can be implemented. However, in practice, only operations supported by specialized hardware run at acceptable speeds for RRSAS purposes. These include both binary and gray scale morphological operations (dilations and erosions), thresholding, and simple arithmetic (Serra, 1982).

CASK LOCATION

When commanded to locate the shipping cask, the vision system moves the robot arm to a position allowing both cameras to view the nominal position of the first handling lug with a 40-in. field of view. The system then acquires images from both left and right cameras. Each image is processed to determine, if possible, the two-dimensional location in the image of the target, the center of a dark area surrounded by a bright area. If the target is successfully located in both images, previously determined camera calibration coefficients are used in a triangulation process to find the three-dimensional coordinates of the lug center in the robot base coordinate system. If the lug center is not successfully located in both images, an error recovery procedure is invoked. The position of each of the three lugs is found in this way. If checks on the lug locations are satisfactory, the three lug positions are sent to the client program with a status code indicating successful location (see the Error Detection and Recovery section below).

Figure B-2. RRSAS Vision System Overview

CALIBRATION

The calibration process generates the coefficients relating two-dimensional image locations to three-dimensional locations in the world. Calibration requires a series of data sets; each data set consists of the three-dimensional coordinates of a point and the position of the point in the left and right camera images. A lug, like those on the cask, is mounted on a white wall to serve as a calibration target. During calibration, the vision system moves the robot to a start position at which the target is approximately centered in both camera images. The system then moves the arm to a series of positions displaced from the start position by varying distances in x , y , and z . (The fourth degree of freedom, θ , is not exercised.) At each position, the vision system acquires a pair of images and locates the lug center in each image. The coordinates of the lug center at each position are the x , y , and z displacements in robot base coordinates, from the center of joint four, which is the robot's elbow, to the lug center. The resulting data are passed to the calibration routine, which finds the camera calibration coefficients by performing a least-squares-error fit to a set of linear equations containing the calibration data.

The resulting frame of reference has its origin at joint four, rotates with joint four, and is aligned with the robot base frame when joint four is at the calibration position. Subsequent triangulation operations in the IFC find the location of a point in this frame. The host computer transforms points from the camera coordinate system into the robot base coordinate system.

IMAGE ACQUISITION AND TARGET LOCATION

Both cask location and calibration depend heavily on locating the lug center in images. The following procedures are used to acquire images that compensate for lighting variation and to isolate the lug center.

As part of the image acquisition process, the gain of the image digitizer is adjusted so that the histogram of pixel intensities is well distributed over the possible range. In an iterative process, the system acquires an image, examines the histogram, and modifies the digitizer gain until the acquired image is acceptable. After digitizer settings are selected for both cameras, images from each camera are acquired in quick succession. Because the robot is slowly hunting around a nominal position, it is necessary to obtain the left and right camera images with minimum time difference to minimize the possible change in stereo baseline.

The first image processing step is to convert the gray scale image to a binary image. A threshold is selected by processing a histogram of the pixel intensity in the area of interest; confining the processing to this area eliminates the background clutter above and below the cask. The handling lug is the darkest object in the area of interest; the image histogram is bimodal. The process searches the histogram for the minimum value between the intensities corresponding to the lug and those for the cask body. The lug group must include at least as many pixels as the minimum expected lug size. The image is binarized with this threshold.

The image is also inverted, i.e., dark pixels become foreground, since the object of interest is dark.

The next processing step is lug isolation from other foreground pixels. A dilation operation fills in any small holes in the foreground groupings. Then, an erosion operation eliminates groupings much smaller than the expected lug size. Finally, another dilation returns any remaining groups to their original size. Normally, only one group remains in the area of interest. If this group is within acceptable size limits and its shape is approximately square, its center is identified as the lug center. If there are no groups, or more than one of the right size and shape, the routine reports a failure to locate the lug; this leads to attempted error recovery.

ERROR DETECTION AND RECOVERY

The RRSAS vision system can detect several indications of error. If the lug center is not successfully located in both images, the system moves the robot slightly and repeats the image acquisition and analysis process. If not successful after three tries, the system reports a failure to the client process. In the early phases of vision development, the system has been occasionally confused by shadows on the cask body; often this shift in viewing position has allowed the lug center to be located. The current vision algorithms described above have eliminated the shadow problem.

In addition, each lug position is checked to confirm that it lies within 18 in. of the nominal position and within 3 in. of the nominal height. As a further check, the distances between lugs are calculated to ensure that they are approximately correct. These verification steps minimize the probability that the robot will be directed to begin operations in an incorrect location. However, no automatic recovery is attempted if lug locations are invalid.

RESULTS

The RRSAS vision system has been operational for approximately 1 yr and has achieved the requirements identified in the Task Description section. The system reliably locates the mock-up cask, determining the position of each lug within 0.2 in. Seventy-five percent of the locations are within 0.1 in. No significant difference in performance is observable under lighting variation. Time required for cask location is 1 min, 15 s. As a result of the error detection procedures, the vision system has never reported a successful cask location while returning an incorrect cask location. With the current algorithms, the vision system has located the cask 112 times; the only failures resulted from an image digitizer hardware failure.

Over a 10-wk period, the cask has been left in one position to allow evaluation of vision repeatability and stability. The system was not recalibrated during this time. The resulting data are summarized in Table B-1. Note that no variation in location accuracy is evident during this time. A theodolite measuring system is used as an independent check of vision accuracy; for each lug, the mean location, as measured by the vision system, agrees with the theodolite measurement to within the

Table B-1

Repeatability of Cask Location

Lug	Period	X-Axis Mean	X-Axis Std Dev	Y-Axis Mean	Y-Axis Std Dev	Z-Axis Mean	Z-Axis Std Dev
0	Ten Weeks	-101.23	0.05	-8.02	0.07	-18.89	0.05
	First Week	-101.22	0.05	-8.05	0.07	-18.89	0.04
	Last Week	-101.24	0.05	-7.99	0.07	-18.88	0.06
1	Ten Weeks	-41.31	0.04	-5.07	0.06	-19.06	0.04
	First Week	-41.31	0.05	-5.09	0.06	-19.06	0.03
	Last Week	-41.31	0.04	-5.04	0.05	-19.05	0.05
2	Ten Weeks	-42.99	0.05	28.38	0.05	-19.22	0.04
	First Week	-43.00	0.03	28.38	0.07	-19.22	0.03
	Last Week	-43.01	0.03	28.37	0.05	-19.22	0.04

theodolite accuracy (0.1 in.). Another check on the vision system's relative accuracy is the distance between lugs. The actual distance between Lug 0 and Lug 1 is 60 in.; the mean distance measured by the vision system is 59.99 in., with a standard deviation of 0.03 in.

After deciding to use arm-mounted cameras, there has been some concern about the effects of arm motion and vibration. However, the results have been favorable: camera calibration has been stable, and the CCD cameras have shown no adverse effects from the vibration.

REFERENCES

Machine Vision International, 1986. "Genesis Systems Operations Manual," Ann Arbor, MI.

Serra, J., 1982. *Image Analysis and Mathematical Morphology*, New York: Academic Press.

Thunborg, S., 1988. "RRSAS Project: A Real Time Sensor Driven Robotic System," paper presented at Robots 12/Vision '88 Conference, sponsored by the Society of Manufacturing Engineers, Detroit.

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APPENDIX C

SUPERVISORY CONTROL FOR A COMPLEX ROBOTIC SYSTEM*

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ABSTRACT

The Robotic Radiation Survey and Analysis System (RRSAS) investigates the use of advanced robotic technology for performing remote radiation surveys on nuclear waste shipping casks. Robotic systems have the potential for reducing personnel exposure to radiation and providing fast, reliable throughput at future repository sites. A primary technology issue is the integrated control of distributed, specialized hardware through a modular supervisory software system. Automated programming of robot trajectories, based on mathematical cask and robot models coupled with sensory feedback, enable flexible operation of a commercial gantry robot with the reliability needed to perform autonomous operations in a hazardous environment. Complexity is managed using structured software engineering techniques, resulting in the generation of reusable command primitives that contribute to a software parts catalog for a generalized robot programming language.

*Paper presented at Robots 12/Vision '88 Conference, sponsored by the Society of Manufacturing Engineers, Detroit, Michigan, June 6-9, 1988.

INTRODUCTION

This appendix discusses the supervisory software environment of the Robotic Radiation Survey and Analysis System (RRSAS). Of particular importance is the development of software to support the automatic programming of detailed robot trajectories based on models of the robot and its environment. Sensors are used to correct for errors in the models. Model-based robot control is critical for such application, since personnel access to radiation environments for manual programming of robots will be severely limited.

In the following sections, the problems associated with developing complex software environments are explored, particularly as they relate to the model-based control of robotic systems. The characteristics of quality software and the goals and principles of software engineering that have been used in the RRSAS development process are discussed. This is followed by a description of the software design methodology and its application across all levels of programming, ranging from modeling of the shipping cask and automatic programming of robot motions at the highest task level, to real-time force control at the lowest robot level. Finally, it is shown that the resulting implementation may be considered a paradigm for controlling any complex robotic system.

Evolution of complex computing environments has led to hierarchical distributed systems with multiple heterogeneous computers. These computers execute specialized concurrent functions, often in real time, while communicating with one another in a coordinated fashion. Such architectures lend themselves to robotic systems containing diverse devices that must be integrated with a manipulator to perform specific tasks. The RRSAS is an example of a hierarchical distributed computing system that addresses five well-defined operations for handling nuclear waste shipping casks at repository sites:

- Cask location using vision,
- Cask identification using bar code labels,
- Video survey for mechanical damage,
- Geiger counter survey for beta/gamma radiation analysis, and
- Contact swipe survey at random cask surface locations for alpha/beta/gamma radiation analysis.

A large 20-ft x 40-ft gantry robot performs these operations. Each operation possesses a set of control requirements (Thunborg, 1987) that must be handled by a supervisory computing system. The supervisory computer communicates with specialized hardware, e.g., a robot controller, vision system, force sensor, bar code reader, Geiger counter, and swipe reader. Communication occurs by passing messages of command primitives to each system component. All subsystem activity is initiated by the host computer, which may communicate with several devices simultaneously, thus providing a parallel control architecture.

The technical challenge associated with developing a supervisory software environment for the RRSAS results from the software, which is the integrating agent for the system. Software complexity could not be avoided, due to the innate complexity of the RRSAS environment and the requirement for

model-based automatic control. Therefore, an approach that resulted in controlled complexity was adopted, and high system reliability was achieved through error detection and recovery. In addition, the hierarchical modularized approach to the software architecture employed in this research produces selected system-independent software modules reusable in other robotics projects. This represents the beginning of a system-independent library of software modules. One goal of robotic systems development at Sandia National Laboratories (SNL) is the generation of a parts catalog for robotic systems software to facilitate the development of future advanced robotic systems. The supervisory software development associated with the RRSAS contributes to that goal.

COMPLEXITY ISSUES FOR ROBOTIC SOFTWARE

The special nature of robotic systems presents unique, complex software problems. First and foremost, robotics software must interact with a richer variety of intelligent subsystems than most application environments. The RRSAS configuration illustrates this with five different external devices, including a vision system, bar code reader, Geiger counter, swipe reader, and force sensor. This diversity poses difficulties for software development, particularly when all of the subsystems must be integrated. New software is usually needed for each piece of new hardware. Therefore, the software designer must become intimately familiar with many different types of hardware or treat them as black boxes, relying on proprietary vendor firmware and documentation. If the firmware does not function as advertised, the software designer must determine the true capabilities of each device and compensate for poor hardware and inadequate firmware. Interfacing with other incompatible subsystems requires a communications code that must handle protocol and timing differences. Frequently, the software design cannot be completed or implemented until the hardware is installed and physically networked together. The software developer must first experiment with uncertain device behaviors before committing to a design that has only been worked out on paper.

Another unique aspect of robotic systems is the physical interaction between the robot and its environment to perform tasks normally done by humans. This interaction requires that the software models the world in which the robot exists to automatically program appropriate robot motions. This model includes geometric and physical knowledge of the objects in the robot's workspace, as well as a kinematic model of the robot itself. In the RRSAS, a mathematical model of the shipping cask and a model that relates the kinematics of the gantry robot to its approaches and to each cask surface are critical in performing the random swipe survey.

Motion and grasp planning are key tasks of robotics software that require a good world model. Generated plans must deal with issues such as safety, stability, reachability, speed, accuracy, and joint limits. Trajectories must be coordinated with knowledge of the environment to achieve correct arm position and orientation while avoiding obstacles. Different types of motion must also be handled. If a planned path has no known obstacles, and the robot is not interacting with other objects, free motion can be used to take the quickest and most direct route available toward the destination. If the robot interacts with other objects, guarded motion that may be slowed or terminated on the basis of sensory data should be used to

facilitate proper contact with these objects. In the RRSAS, guarded motion occurs during the contact swipe survey to move in and touch the shipping cask. When a certain amount of force has been detected between the swipe and the cask's surface, the motion is terminated. Finally, compliant motion is used to swipe the cask's surface. This type of motion must conform with forces encountered between the swipe and the cask to maintain constant pressure on the surface. Using guarded and compliant motion implies the need for real-time sensory information and feedback. These are dynamic aspects of the world model. The software that controls such real-time physical processes performed by the robot cannot be suspended and later resumed while the computer is servicing other programs. All of these modeling issues contribute to complexity when designing software for an integrated robotics system.

A third aspect of robotic systems that contributes to software complexity is the need for extensive error detection and recovery procedures. When the system architecture contains many distributed components that interact with one another, the number of different system states can be large. The software design must anticipate these states and provide appropriate responses to each. The strong interaction between the software and the physical system it controls makes error recovery for robotic systems difficult to implement. It requires the most current knowledge of the state-of-the-world model, which must be dynamically updated during each robotic operation. Error handling is particularly critical for applications like the RRSAS, where the robot is performing remote surveys in a hazardous environment. However, the quantity of code implemented to achieve high reliability can equal or exceed the code that performs the actual system tasks. Approximately 50 percent of the code in this module performs error detection or recovery operations.

Aside from these unique aspects, robotic software design also inherits the problems associated with any complex software system. Most systems are initially poorly specified and, thus, the software must be designed for extensibility, adaptability, and maintainability. Using operating system software, e.g., a kernel, compiler, or window manager, to handle code generation, computer resource and device management, graphics, or communications may introduce errors that are difficult to find and work around. Real-time control often demands special hardware and system software support, which requires expertise in interrupt-driven programming and assembly languages. User interfaces are time-consuming to implement and require extensive coding to be flexible enough for all levels of usage, yet robust enough to prevent accidental or deliberate damage to the system.

Finally, the software designer must have a mechanism for dealing directly with complexity. Designing and implementing thousands or possibly millions of lines of code to solve complex problems requires intellectual and physical capacities that exceed those of a single person, unless the solution is broken down into manageable parts. A divide-and-conquer strategy is the only way to successfully build a complex system. Software design methodologies can provide a formal mechanism for implementing this strategy and for ultimately controlling complexity.

MANAGING COMPLEXITY

Designing the complex software environment needed to control the numerous intelligent devices comprising the RRSAS has posed a challenge. The concept of embedded intelligence has resulted in the development of many systems whose distributed computing potentials have not been fully utilized, because the resulting complexity has outgrown the ability to manage the system. This inability to develop software that effectively manages subsystems integration required to perform complex tasks is part of a dilemma commonly referred to as the software crisis (Pressman, 1982). The development of software tools has not kept pace with the development of computer-driven hardware, making it difficult to cope with the diversity and complexity of large-scale systems like the RRSAS.

A major requirement for the RRSAS is high reliability to prevent personnel exposure to radiation in hazardous environments where such robotic systems must perform. However, uncontrolled complexity results in unreliability. To develop the complex yet reliable software system required by the RRSAS, software development has been patterned after the development of complex hardware systems, in which relatively simple components are combined to achieve complex behavior and desired functionality. This enables isolation of related functions, simplification of their interfaces, and thorough testing of individual components. System complexity is ultimately achieved through a linear combination of simple subsystems with verifiably correct behavior.

Four primary software engineering principles are generally regarded as critical to good design: modularity, locality, abstraction, and information hiding (Pressman, 1982). Modularity refers to purposeful decomposition of software into distinct elements that are integrated to satisfy problem requirements. Modularity is the software attribute that allows a program to be intellectually manageable. Locality is directly related to modularity in that it determines the degree of module independence. Locality is defined as achieving a high degree of independence by developing modules that perform single-purpose functions and require minimal interaction with other modules. Applying the principle of locality, therefore, results in modules with strong internal cohesion and loose coupling.

The principles of abstraction and information hiding refer to extracting essential properties while omitting inessential details. In the context of software development, abstraction and information hiding permit the software designer to concentrate on a problem solution at one level of generalization at a time while delaying consideration of lower-level details. Each step in the software engineering process is a refinement in the level of abstraction of the software structure. At the highest level, the software system structure is described in broad terms, using the language of the problem environment. At lower levels, a more procedural orientation to software structure is taken, where problem-oriented descriptors are coupled with implementation-oriented descriptors to define algorithmic solutions. Finally, at the lowest levels, the software structure is described in the direct implementation terms of data structures and programming language primitives. Such stepwise refinement (further discussed below) is closely aligned with modularity, because it results in a factored structure that distributes levels of control and decision making into modules.

Information hiding suggests that procedures and data contained within a module should be inaccessible to other modules that have no need for such information. The term "hiding" implies that effective modularity can be achieved by defining a set of independent modules that communicate only the information necessary to achieve software function. Thus, abstraction helps to define the procedural or informational entities that comprise the software, and information hiding defines and enforces access constraints to both procedural detail and local data structures contained in each module.

Numerous methodologies have been proposed (Pressman, 1982; Wirth, 1971; Yourdon and Constantine, 1979) for software development. These methodologies, if properly adhered to, encourage and enforce the application of the four software engineering principles: modularity, locality, abstraction, and information hiding. They also help produce detailed code documentation, which is necessary for the proper coordination, control, and management of complex software environments.

THE RRSAS SOFTWARE DESIGN METHODOLOGY

The RRSAS is a complex robotic system with a distributed multiprocessor computing environment capable of model- and sensor-based control. The RRSAS achieves high system reliability by detecting subsystem errors and recovering from those errors. A software environment that uses procedural knowledge to plan actions is important to the consistent operational behavior of the RRSAS. The RRSAS anticipates the consequences of actions to uncover and deal with error situations.

To create a software environment supporting the RRSAS objectives and exhibiting the properties of modularity, locality, abstraction, and information hiding, a methodology has been developed that embodies concepts from top-down structured design (Yourdon and Constantine, 1979), stepwise refinement (Wirth, 1971), and bottom-up implementation. This approach is well suited for designing task-driven robotic systems with many intelligent special-purpose devices, which must be integrated to form a cohesive environment. Top-down structured design decomposes a system by making each action of the system a module. This leads to program modules that closely reflect system function, or a function-oriented approach. At the highest level, the modules represent the overall function of the system. For the RRSAS, the highest level is performance of remote radiation surveys on nuclear waste shipping casks. At lower levels, successively more-detailed functions are implemented that, when combined, perform this high-level action. A low-level RRSAS primitive example would be to move the robot from point A to point B.

Stepwise refinement develops the intermediate-level modules that provide the bridge between the highest and lowest levels by successively refining additional levels of procedural detail. Initially, a software control program named supervisor is defined. Then, each task invoked by the supervisor is expanded in top-down fashion. Additional levels of refinement occur until a level of detail has been achieved that results in single-function modules which cannot be logically decomposed any further.

Refinement is accomplished by selecting, at each step of the software system design process, the next lower-level procedural abstraction and investigating its implementation by making lists of the tasks that must be accomplished in the procedure. Using these lists as a guide, and allowing the problem structure to determine software structure, further lower-level abstractions can be specified. This process is iterated until sufficient refinement has been achieved, resulting in a hierarchy of abstractions that can be represented by a module dependency diagram, reflecting the completed design.

Bottom-up implementation of this software system design allows immediate interfacing with the system hardware. Immediate interfacing can quickly address problems associated with unpredictable device behaviors. Components not designed for compatibility and having insufficient documentation result in problems that can only be dealt with through experimental programming. This programming should be done early in the implementation phase to facilitate design changes resulting from new knowledge gained about each subsystem.

Application of the Design Methodology

Three primary objectives have guided the overall RRSAS software system design procedure. The first objective is to provide a robotic system that executed all cask radiation survey operations automatically, while keeping the operator informed of the system status and survey results, using windows, menus, and graphics. This requires a software system that provided a high degree of hardware integration. The second objective is to include robust error detection and recovery capabilities. This requirement for error detection and recovery reflects the need for high reliability and autonomous operation in a hazardous environment. The third objective is to create a generalized software development environment as opposed to a project-specific control program. Future robotic tasks using the same or similar hardware could then be rapidly implemented with the software tools produced.

Application of the top-down design and bottom-up implementation methodology discussed above has resulted in well-defined software tasks that map onto the appropriate hardware subsystems. This definition produces a hierarchical architecture that reflects the engineering principles of modularity, locality, abstraction, and information hiding. Figure C-1 shows the distributed architecture with the software task hierarchy superimposed over the hardware.

The man-machine interface task (MMI Task) at the top of the hierarchy provides the primary operator interface to the system. This task hides the MMI data structures, or menu displays, and windowing system interfaces from the other supervisory components. It handles operator inputs through mouse button picks and communicates menu selections to the other tasks, triggering appropriate actions.

The Supervisor Task on the host computer is the primary RRSAS control program. It is decomposed at the highest level of abstraction into task-oriented modules which, when properly combined, accomplish each of the five survey operations discussed above, as well as system startup and shutdown. These RRSAS function-oriented task modules--init, vision, barcode, radsurvey,

Figure C-1. RRSAS Architecture

swipesurvey, and wrapup--are decomposed into successive levels of abstraction, as described above, until a level is reached that contains a set of task- and device-independent modules, as shown in Figure C-2. These modules contribute to the generalized software environment by providing reusable tools for basic robotic functions. The generic modules of Figure C-2 are decomposed further until, at the lowest-levels of abstraction, modules containing device-dependent code result. These lowest-level modules handle operating system interfaces and communication protocols for the other intelligent hardware subsystems present in the overall configuration. A detailed example of how top-down design is employed to produce a complete module dependency diagram for the random contact swipe survey, or swipesurvey, is discussed in the following section.

Other task modules in the software hierarchy provide specialized services for the supervisor or control other subsystems, such as a Monitor program, which is downloaded by the supervisor to execute on the robot controller. The Monitor program, written in the robot language CIMPLER (CIMCORP, 1986), serves as a device driver that handles all robot primitives sent by the supervisor by parsing each command and calling the appropriate robot-control subroutines. These robot-control subroutines execute the specific CIMPLER language statements that drive the servos and move the arm.

A Swipe Task is initiated by the swipesurvey module on the host computer. It executes on a dedicated PDP/11 with RT-11 processor environment and provides force-controlled movement of the robot arm for the random contact swipe survey. This computer serves as a force servo control system, which monitors a force sensor mounted on the wrist of the robot and makes real-time trajectory corrections to the robot arm. The corrections are based on the contact force detected between the robot's end effector, or swipe planchet, and the cask, and serve to produce a constant force swipe (Petterson and Jones, 1987). This task, therefore, hides all of the algorithmic details and hardware-specific knowledge of force control and real-time trajectory correction from the supervisor. The supervisor simply has knowledge of a procedural level of abstraction (the doswipe module in the swipesurvey hierarchy) that commands the force control subsystem to perform a swipe at a location and in a direction, based on the cask model, which is determined by the swipesurvey task module in the supervisor. This force control task, in turn, has its own abstraction hierarchy containing the necessary modules and dependencies to accomplish its specified functions.

The Vision Task runs on the host computer in conjunction with the Supervisor Task. It provides an interface to the low-level vision functions, which are performed by a separate computer containing special-purpose computer vision hardware and software. The supervisory vision module sends high-level commands, such as "locate cask," to the Vision Task. The Vision Task decomposes this command into a sequence of robotic actions and image analysis operations to ultimately accomplish the supervisor's request (Ray, forthcoming).

Finally, four other auxiliary tasks, or Graphics Tasks, reside on the host computer, as shown in Figure C-1. During the initialization phase, the Supervisor Task activates the Graphics Tasks, which generate appropriate graphics windows when signaled to do so. They produce three-dimensional graphics representations for real-time data displays of radiation readings

Action Primitives:

pickupeff	() - Pick up an end effector
putdowneff	() - Put down an end effector
robothome	() - Send robot to a safe home location
robotmove	() - Move robot to a specified destination
robotrmove	() - Relatively move robot by specified offsets

Environment Primitives:

checkswitch	() - Check a hardware micro-switch for end effector station status
cmpclthome	() - Compare robot's current location to the home location
gripperempty	() - Determine gripper status
whateff	() - Determine what end effector is in the gripper

I/O Primitives:

openport	() - Open a serial port for communication
readport	() - Read from a serial port
writeport	() - Write to a serial port

Figure C-2. Generic Modules for a Robotic Environment

and random contact swipe locations. Figure C-3 illustrates an example of the graphics generated by these tasks.

Detailed Example - Random Swipe Survey

The random contact swipe survey is the most technically challenging RRSAS operation and, therefore, provides the most comprehensive example of how a task is decomposed, using this methodology. The specifications for this operation can first be reformulated into a description of subtasks that identify the subordinate abstractions required. Figure C-4 contains this list of descriptions and the corresponding highest-level modules derived from it. Several operational characteristics of the swipe task are captured in the task descriptions.

As shown in Task 1, swiping requires the use of commanded, model-based robot motion rather than conventionally taught motion for path determination, because the swipe points must be selected randomly for each task survey. In addition, Tasks 2, 3, and 6 show that the robot's location with respect to the task must be known to automatically determine unobstructed travel paths, when moving from one swipe point to another with swipe-dispensing moves in between. Messages must be sent to the force control computer when the swipe planchet has been positioned over each swipe point, and the force control computer must perform the real-time constant-force swiping action. Prior to each swiping action, graphics displays (Task 5) must be generated showing each swipe point location on the task. The operator can verify that the arm is moving to the correct location, which is unknown in advance, by observing the display and subsequent arm motion. Upon completion of the survey, the Supervisor Task directs the swipe reader to analyze the swipes in Tasks 7 and 8. Thus, to execute a swipe survey, the Supervisor Task must coordinate the actions of the robot controller, force-control computer, swipe reader, and graphics tasks.

Figure C-5 is the module dependency diagram of the swipesurvey task module on the host computer. Each of the higher-level modules represents an abstraction level that must be decomposed iteratively using stepwise refinement to complete the diagram. Figure C-5 shows the decomposition of the swipesurvey supervisory module down to the lowest levels. This hierarchy provides a complete structural representation for the swipe survey software.

The following section will focus on the processing details of each module individually to provide procedural representation. A precise specification of each module includes sequence of events, exact decision points, repetitive operations, references to all subordinate modules, and data organization and structure. Specifications for each RRSAS module are spelled out in the source code level files for these modules. Specifications for the higher-level modules are relatively straightforward because, in many cases, they consist only of call sequences to lower level modules. The lowest levels, however, must interface with the operating system and external devices and, therefore, require careful consideration.

The specifications for each of the modules in Figure C-5 are initially created by writing source-code-level files containing only comment statements. An extended comment statement at the beginning of each module serves as a header containing all the information needed to understand what the

Figure C-3. Swipe Survey Graphics Display

Task Description	Module(s)
(1) Generate random sets of swipe locations evenly distributed over the surface areas of the cask with an algorithm which utilizes a mathematical model of the cask.	genswipepts initialize montecarlo
(2) Generate robot approach vectors for each swipe point which optimally orient the arm and swipe tool to reach all physically accessible surfaces while avoiding collisions.	addapprmts
(3) Compute the inverse kinematics for the robot arm in order to transform swipe point locations and their corresponding approach vectors into the robot's joint coordinate system, with full knowledge of robot joint limits and the cask's location through vision.	touch
(4) Optimize the path followed by the robot around the cask as it takes swipes by sorting the points based on surface location.	optpath
(5) Graphically display the cask and the selected swipe points on its surface.	(separate tasks)
(6) Retrieve a swipe from the dispensing magazine, move to a swipe location, perform the swipe and return the used swipe to a contamination magazine.	swipestartup swipesequence swipeop
(7) Deliver the full contamination magazine to a swipe radiation detection system (reader).	getcanister
(8) Direct the swipe reader to analyze each swipe and return the results to the host for display and archival purposes.	canberra

Figure C-4. List of Swipe Survey Tasks

Figure C-5. Module Dependency Diagram for Swipesurvey

Figure C-5. Module Dependency Diagram for Swipesurvey (Concluded)

module does and how it should be used. Then, a sequence of comment statements describes each step to be performed by the module, the data structures that are needed and how they are affected, and the external effects, if any, that occur when this module is executed. Once all specifications are written for each module, the data and control structures for each module are defined, using standard programming language constructs. Figure C-6 illustrates a typical RRSAS software module. Most of the implementation is performed using C programming language in a UNIX environment.

The modules of Figure C-5 are implemented in a bottom-up fashion. This allows systematic debugging at progressively higher levels of abstraction by building test programs to exercise the functions of each module. Once a set of related modules has been tested individually, their dependencies and interfaces are tested. This process is iterated until the top of an abstraction hierarchy representing one of the survey operations is reached. The next operation is also debugged by starting at the bottom of its module dependency diagram and once again climbing the hierarchy. Because tasks frequently share many of the same modules at lower levels, debugging of subsequent operations has become easier, since only the higher task-specific modules required testing. In addition, milestones have been established throughout the course of development that require complete demonstrations of each operation as it is added to the system. This process results in stages of stability that eliminate the majority of software bugs by the time the entire configuration is completed.

ERROR RECOVERY TECHNIQUES

A primary consideration in designing and implementing the RRSAS software system has been error detection and recovery. Error detection is performed by comparing the results of module execution with models of what should have resulted. Components contributing to the error recovery environment include binary microswitch sensors monitored by the Supervisor Task to determine the state of the world. The microswitches provide the current status of end-effector stations and other critical mechanisms, i.e., swipe dispenser, robot gripper, and pneumatic locks. In addition, an interrupt signal line from the robot controller to the host serves as a real-time alarm to alert the Supervisor Task when the robot has stopped unexpectedly. Other modules, such as those contained in the computer vision and force control subsystems, incorporate expectation-driven error detection. For example, if the computer vision subsystem executes properly, but analysis of the captured image does not contain the type of information anticipated, an error situation is signaled. Hierarchical error analysis detects failures at every level of abstraction by encapsulating modules in a control loop that checks error status after each incremental operation. This procedure provides maximum flexibility to detect error conditions at the levels where they occur, allowing for local recovery and avoiding the need to redo an entire operation when a small step in its sequence has failed.

The primary sources for failure observed in the RRSAS include communication errors between the supervisor and other subsystems, unexpected stoppages due to subsystem failures (e.g., failure of the vision subsystem to locate expected visual reference features and thus not locate the cask), and microswitch signals indicating invalid system status. In many cases, the problem is caused by a minor hardware or mechanical malfunction that can be

```

/*****
* Project Name: RRSAS
* Module Name : swipesurvey
* Path Name   : /usr/users/miller/gantry/rrsas swipesurvey.c
*
* Module Type : subroutine
* Form of Call: swipesurvey(&err);
* Function    : top level routine for swipe survey operation
* Environment : UNIX
*
* Inputs      : global data structures
* Outputs     : int err - error return code
* Externals   : genswipepts, swipestartup, swipesequences, getcanister,
*               canberra
*
* Author      : David J. Miller
*               Sandia National Laboratories
*               May, 1987
*****/

/* declare include files containing global data structures */
#include "/usr/users/miller/include/rrsas errorcodes.h"
#include "/usr/users/miller/include/rrsas vision.h"
#include "/usr/users/miller/include/rrsas swipe.h"
#include "/usr/users/miller/include/rrsas robot.h"
#include "/usr/users/cbselle/gantry/abg.h"

swipesurvey(err)
int *err; /* argument is a pointer to an error return code */
{
    int efftype; /* end effector ID code */
    int type; /* error recovery type */
    int saverr; /* slot for saving error code */

    genswipepts(); /* monte carlo sequence */
    swipestartup(); /* initialize data structures */
    robothome(err); /* make sure robot is home */
    if ((*err) != NOERROR) return; /* bail out if unsuccessful */
    gripperempty(err); /* make sure gripper is empty */
    if ((*err) == GRIPPERNOTEMPTY) /* if not, free it up */
    {
        (*err) = NOERROR; /* first clear the error flag */
        whateff(&efftype); /* find out what it's holding */
        putdowneff(efftype, err); /* put it down */
        if ((*err) != NOERROR) return; /* bail out if unsuccessful */
    }
    else (*err) = NOERROR; /* gripper free - clear flag */
    robotjamove(safehome, err); /* position arm under swipe */
    if ((*err) != NOERROR) return; /* bail out if unsuccessful */
    sinit(err); /* chk station microswitches */
    if ((*err) != NOERROR) /* switches signal an error */
    {
        saverr = (*err);
        xmtrcvmsg(TURNONCMD, err); /* restore switch status */
        (*err) = saverr; return; /* bail out */
    }
    swipesequences(err); /* do 40 swipes */
    if ((*err) != NOERROR) return; /* bail out if unsuccessful */

    continu = NO;
    while (continu == NO) /* deliver canister to reader */
    {
        printf("Deliver Canister to Canberra...\n"); getcanister(err);
        if ((*err) != NOERROR) { printf("Delivery FAILED!\n");
            initrecovery(&type, (*err)); dorecovery(type, err);
            if ((*err) != NOERROR) return; }
        else { printf("Delivery COMPLETED\n"); continu = YES; }
    }
    xmtrcvmsg(TURNONCMD, err); /* restore switch status */
    return; /* normal return */
}

```

Figure C-6. Typical RRSAS Module - Swipesurvey

corrected automatically. For example, if the computer vision system fails to locate an approximate visual reference point during its cask-finding task, the robot-mounted cameras will be automatically shifted slightly, and the vision process repeated.

Other cases, such as repeated failure to recover automatically, would require manual intervention. A standard procedure is always invoked when an error requiring operator attention is detected. This procedure informs the operator of the cause of the failure and provides four recovery options. The operator may choose to retry the failed operation, skip it and move on to the next operation, perform the operation manually, or abort the task. Error recovery has proven to be a powerful approach to improve system reliability. Because the system can correct failures of individual components, it can tolerate subsystem failures while maintaining high overall system reliability. Success is gauged by whether the operator can restore the system to normal operation without entering the hazardous environment.

DISCUSSION AND CONCLUSIONS

The RRSAS was successfully completed in August 1987 and is currently operational. The system successfully uses models of the robot and cask to automatically program robot trajectories to perform radiation survey tasks. While sensors provide corrections to the robot trajectories to compensate for small errors in the models, good model information is important for fast, efficient operation. The robot system can perform random swiping operations at least as fast as a human and in a far more consistent fashion, by employing good geometric information to drive the robot, and by using force sensing to make only minor trajectory perturbations and to maintain the specified contact force. In addition, error recovery has been proven to provide high overall system reliability. Since completion of the RRSAS, many system demonstrations have been performed. It is not uncommon for an observer to conclude that the system works without error, even though subsystem errors did occur but were detected and corrected automatically by the system.

RRSAS software design and implementation phases were performed during the last 12 months of this 18-month project. These phases followed six months of system specification and preliminary installation of some of the major hardware components, including the gantry robot and software development system. Additional hardware design and installation of specialized subsystem components have been performed in parallel with the software effort and were integrated on a task-by-task basis. Application of the top-down design/bottom-up implementation methodology enables software development to keep pace with hardware installation and is the primary reason that the software has been completed on schedule. The final host computer hardware configuration, a SUN 3/160 work station, was not delivered until six months before the project completion date. The software has been easily ported from a DEC Micro-VAX, used for initial development. The final configuration fulfills the objectives of providing a fully automatic robot system with robust error recovery. The software satisfies design specifications and proves to be extremely reliable, with few bugs detected after the acceptance demonstration.

The resulting supervisory software architecture clearly reflects the software engineering principles of modularity, locality, abstraction, and

information hiding. The main Supervisor Task alone consists of approximately 10,000 lines of code decomposed into over 200 modules. This implies that the average module length is 50 lines of code, or a single page of printout; the ideal length for easy comprehension and modification. In addition, because the lower half of the module dependency diagram for each of the major survey operations is nearly identical, decomposition has been performed in a logical and consistent fashion by iteratively hiding lower-level details from successively higher levels of abstraction.

The production of generic robotic primitives also illustrates these concepts and provides building blocks for future development. In fact, the entire RRSAS hierarchy, as shown in Figure C-1, can be abstracted to a higher level that represents a generic robotic system environment. Figure C-7 illustrates this architecture, which consists of three primary components. The first layer, the Project-Specific Global Task Definitions, is derived from the top-down decomposition of the specifications (highest-level abstractions). An example would be the set of cask survey operations and the subtasks specific to each of these operations. The second layer, the Device- and Task-Independent Primitives, represents functionality present in any robotic system regardless of hardware implementation or purpose. An example of these primitives would be the RRSAS modules listed in Figure C-2. The third layer, the Device-Dependent Code device drivers, is the initial result of bottom-up implementation. This device-dependent software logically represents the functional definitions of the hardware, including command primitives, communications protocols, and interrupt-driven, real-time sensor control. An example of this last component is the real-time force-control task used to direct the swiping operation.

With this paradigm, it should be possible and advantageous to model and build any hierarchical robotic system. Once the middle layer of generic primitives has been defined and implemented, it can be ported to any new system under development. Also, once a complete system has been implemented, adding task-oriented functionality at the top level is greatly simplified. All modular building blocks will already be available. They simply must be pieced together in the right sequence to produce the desired operation. This could be done interactively by a system operator by using an English-like command language or menu selections. Complex programming efforts could therefore be directed toward making the system more intelligent through the addition of knowledge bases, planning, and sophisticated user interfaces. Incorporating new sensors or mechanical devices at the lowest level will still involve intimate knowledge of the hardware, but this knowledge will be neatly encapsulated in modules that hide this information from the rest of the system and use consistent interface control structures already implemented for other existing devices. All of these concepts are currently being explored as an extension of the RRSAS development work, with the intent of eventually implementing them for diverse robotic environments.

Figure C-7. Generic Hierarchical Robotic System

REFERENCES

CIMCORP Robotics, 1986. "CIMPLER Programming Manual," Doc. Part No. 4316200, CIMCORP, Div. of Wartsila, St. Paul, MN.

Petterson, B. J. and J. F. Jones, 1987. "Force Control of a Robot for Surface Contamination Detection," Remote Systems Technology Division Proceedings, American Nuclear Society Winter Meeting.

Pressman, R. S., 1982. *Software Engineering: A Practitioner's Approach*, New York: McGraw-Hill.

Ray, L. P., "Cask Location with Computer Vision," SAND87-2720, forthcoming.

Thunborg, S., 1987. "A Robotic Radiation Survey and Analysis System," Remote Systems Technology Division Proceedings, American Nuclear Society Winter Meeting.

Wirth, N., 1971. "Program Development by Stepwise Refinement," *CACM*, 14 (no. 4): 221-227.

Yourdon, E. and L. Constantine, 1979. *Structured Design*, New Jersey: Prentice-Hall.

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APPENDIX D

A DISPENSER MECHANISM FOR STACKABLE THIN-EDGED OBJECTS

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INTRODUCTION

The Robotic Radiation Survey and Analysis System (RRSAS) has been developed to perform radiation and contamination surveys on nuclear waste shipping casks upon receipt at geologic waste repositories (Thunborg, 1988). These waste containers must be tested for surface contamination before and after shipping. Presently, repository workers survey the shipping casks for radioactive surface contamination. The RRSAS removes repository workers from the radiation environment and improves the consistency and reliability of the survey operation.

One type of radioactive contamination analyzed by the RRSAS is transferred radiation. Transferred radiation is radioactive contamination, in the form of contaminated particles on the cask surface, that are transferred to personnel or objects which come in contact with the cask. To measure transferred radiation, the robot performs a series of spot contamination checks using a tool designed for wiping down, or swiping, specific areas on the cask surface. This swipe tool, or planchet, (Figure D-1) consists of foam-backed filter paper mounted on a rigid plastic carrier. A handle on the side of the tool opposite the filter paper allows the robot to grasp and orient the swipe material. Planchet legs separate and provide even spacing between the planchets in the magazine, and prevent cross contamination.

Figure D-1. Planchet Used for the Swipe Survey

During the swiping operation, planchets are individually dispensed to the robot from a magazine containing 40 units (Figure D-2). After a swipe is performed, the robot stores the used planchet in a second magazine for future radiation analysis by an alpha/beta/gamma survey instrument. Computer correlation of the known location of each swipe with its associated planchet links a specific amount of transferred contamination with a specific point on the cask.

Existing dispensing mechanisms appropriate for use with the planchets have been found to be cumbersome. For example, the alpha/beta/gamma detector's mechanism for dispensing planchets uses an elevating platform to lift the planchets off a retractable support and dispense them onto a turntable (Figures D-3 and D-4). Such mechanisms, however, could not be used for dispensing the planchets, due to height and size restrictions on the robot gantry.

Figure D-2. Magazines Placed in the Dispenser and Storage Mechanisms

Figure D-3. Dispenser for the Alpha/Beta/Gamma Detector

Figure D-4. Turntable for the Alpha/Beta/Gamma Detector

DESIGN PARAMETERS

A stacking/dispensing cam (Figure D-5) has been designed for use with the stacked planchets. As the cam rotates in the clockwise direction, a groove catches the planchet edge and transports it upward to provide vertical stacking. Likewise, counterclockwise cam rotation transports a stacked planchet downward in a controlled manner. The groove in the dispensing cam is defined by the diameter of the planchet, the distance from the edge of the planchet to the center of the cam, and the planchet thickness. Three cams around the perimeter of the disk ensure even and controlled dispensing. The dispensing rate depends on the revolution speed of the carriers.

The planchet's range of controlled motion is the vertical displacement from the point at which the planchet is first engaged, to the point where it is released, or the vertical distance through which the disk maintains contact with the cam. Planchet alignment is maintained by guide rails alongside the planchets, as shown in Figure D-6.

The planchet-dispensing cycle consists of three phases. In the first phase, or dwell phase, the disk rides on top of the circular region of the dispensing cam. The friction between the disk and the dispensing cam's surface must be kept to a minimum to prevent snagging or possible skipping of the disk along the cam surface (Figure D-6). To reduce friction, the cam surface has been polished. Note that Figures D-6 through D-9 are photographs of a dispenser prototype that has two carriers. The final version of the dispenser has four carriers (see Figure D-11, Items 19 and 24).

The second phase of a dispensing cycle occurs when the leading edge of the groove contacts the planchet and carries it down in a vertical direction (Figure D-7). The leading edge of the groove is the only place where the planchet contacts the cam during this phase (Figure D-5).

The final phase of a dispensing cycle is the drop-off. This occurs when the leading edge of the cam rotates to the point of breaking contact with the planchet (Figure D-7). After release, the planchet drops to a region where it sits until further action is taken (Figure D-8). In the actual dispenser, the planchet sits on a thin retaining platform until the robot grasps and removes it.

Before the drop-off point occurs, the trailing edge of the groove is inserted between the planchet riding in the groove and the planchet that resides above it. This action ensures dispensing of only one disk at a time. To facilitate this action, it is necessary to have some space between adjacent disks. This spacing is provided by the legs on the planchets.

DERIVATION OF DESIGN EQUATIONS FOR THE STACKING/DISPENSING CAM

A distinct relationship exists between the planchet and the cam geometries. The cam groove must accept the planchet edge without interference while maintaining proper planchet motion. The minimum groove is defined by the curve traced by the upper and lower edges of the planchet during its vertical travel. During dispensing, the cam rotates counterclockwise with the reference frame, u , fixed to the carrier and the disk resting on the unit vector, u_2 (Figure D-5).

Figure D-5. Diagram of Disk and Reference Frames

Figure D-6. Dispenser Carrier and Disk in the Dwell Phase

Figure D-7. Dispenser Carrier and Disk in the Second Phase

Figure D-8. Dispenser Carrier and Disk in the Final Phase (Drop-Off)

Figure D-9. Dispenser Carrier and Disk After Drop-Off

Figure D-10. Three-Dimensional Representation of the Cam

Figure D-11. Assembly Drawing of the Dispenser Mechanism

NO	PART/CONTROL NO	DESCRIPTION/MATERIAL	NOTE	QTY	ITEM
2		WASHER, FLAT Ø.190 NOM			89
5		WASHER, FLAT Ø.138 NOM			88
22		WASHER, FLAT Ø.112 NOM			87
17		WASHER, LOCK Ø.250 NOM			86
2		WASHER, LOCK Ø.190 NOM			85
4		WASHER, LOCK Ø.164 NOM			84
11		WASHER, LOCK Ø.138 NOM			83
30		WASHER, LOCK Ø.112 NOM			82
4		WASHER, FLAT Ø.164 NOM			81
9		NUT, HEX .250-28UNF			80
4		NUT, HEX .112(44)-40UNC			79
4		NUT, HEX .138(6)-32UNC			78
6		SCREW, SOC HD CAP .250-20UNC x 2.50			77
11		SCREW, SOC HD CAP .250-20UNC x .875			76
2		SCREW, SOC HD CAP #10-24UNC x 1.75			75
4		SCREW, HEX HD CAP #10-24UNC x .500			74
6		SCREW, SOC HD CAP #10-32UNF x .500			73
4		SCREW, SOC HD CAP #8-32UNC x .750			72
11		SCREW, SOC HD CAP #6-32UNC x .600			71
2		SCREW, PAN HD #8-32UNC x .250			70
3		SCREW, SOC HD CAP #4-40UNC x .750			69
5		SCREW, SOC HD CAP #4-40UNC x .500			68
22		SCREW, SOC HD CAP #4-40UNC x .375			67
6		SCREW, B2" FLAT HD #4-40UNC x .188			66
6		PIN, STRAIGHT Ø.375 x .625 CHES	1		65
9		PIN, SPRING Ø.082 x .375 CHES	2		64
1	354-11-04-001	BOARD, TERMINAL	18	2	63
1	353-11-12-001	BOARD, TERMINAL	16	1	61
1	PT00P-14-125	CONNECTOR, RECEPTICAL	15	1	60
1	PT06P-14-12P	CONNECTOR, PLUG, ELECTRICAL	15	1	59
1	PI-9	CAM, ADJUSTABLE	14	2	57
3	JE-5	ACTUATOR, MECHANISM	13	1	56
3	ISE1-3	MICRO, SWITCH	13	1	55
1	BZ-2F0181-AZ	SWITCH, MICRO	13	2	54
2	K04A	POWER SUPPLY, SOLID STATE RELAY	12	2	53
6	S814FRH-H	BEARING	11	2	52
1	KAC50XPO	BEARING	17	1	51
1	D-186-3	CLEVIS, PISTON ROD	10	1	50
1	D-13498-A	BRACKET, PIVOT	10	1	49
1	D4-DP	CYLINDER, AIR	10	1	48
3	HC100-12-6	COUPLING	9	2	46
1	294-PD	COUPLER, KWIK-CONNECT	8	1	45
1		VALVE, AIR	7	1	44
1	2932	BOX, GEAR	6	1	43
1	41.034.032-00.00-024	MOTOR	6	1	42
3	222-2FR12	DRIVE, RIGHT ANGLE	5	2	40
1	6F3-C037	BELT, TIMING	5	1	39
4	32DF03712	PULLEY, TIMING BELT	5	2	38
1	M59024-10	CLAMP	4	2	36
1	DND-003V-CFF	PROXISTOR, PHOTO ELECTRIC	4	2	35
1	AN7X	SENSOR	3	1	34
					33
					32
					31
					30
1	577817-000	PILOT TUBE 1, PLANCHET MAGAZINE	1		29
1	587258-000	PIN, MAGAZINE, LOCK	1		28
1	587257-000	GUIDE, SIDE, GUARD	1		27
1	587256-000	SUPPORT, SIDE, GUARD	1		26
1	587255-000	GUARD, SIDE	1		25
2	587225-000	DISK, PLANCHET, DISPENSER	2		24
1	587223-000	BRACKET, SWITCH	1		22
1	587222-000	SUPPORT #2	2		21
2	587221-000	SUPPORT #1	2		20
2	587220-000	DISK, SMALL, PLANCHET, DISPENSER	2		19
1	587219-000	SHAFT, EXTENSION	1		18
1	587218-000	SHAFT #2	2		17
2	587217-000	SHAFT #1	2		16
1	587216-000	BLOCK, SENSOR	1		15
1	587215-000	PLATE, DISPENSER, LOCKING, BASE	1		14
1	587214-000	GUIDE #1, RIGHT	1		13
1	587213-000	BRACKET, DISPENSER, LOCK, PUSH	1		12
1	587212-000	BRACKET, POWER SUPPLY	2		11
1	587211-000	PLATE, DISPENSER BASE	1		10
1	587210-000	RETAINER, PLANCHET	1		9
1	587209-000	BRACKET, MOUNTING	2		8
1	587508-000	BRACKET, MOTOR	1		7
1	587207-000	PLATE, LOCK RING	1		6
1	587206-000	PIN, LOCK	1		5
1	587205-000	GUIDE #1, LEFT	1		4
3	587204-000	GUIDE #2	1		3
1	587203-000	BRACKET, CONNECTOR	1		2
1	583173-000	INSERT, MAGAZINE LOCATOR	1		1

NOTES:

▶ PIN ITEMS 20 AND 21 TO ITEM 10, ITEMS 19 AND 24 TO ITEMS 16 AND 17.

▶ MATCH DRILL ITEMS 12 AND 14 AND LOCATE ITEM 22 SO ITEMS 55 AND 56 MAKE CONTACT WITH ITEMS 6 AND 25.

- SOURCE: TURCK
9724-10TH AVE N
MINNEAPOLIS, MIN 55441-5088.
- SOURCE: SENCOR INC
6385 W 74TH ST
BEDFORD PARK, IL 60638.
- SOURCE: STOCK DRIVE
55 S DENTON AVE
NEW HYDE PARK, NY 11040.
- SOURCE: MAXON PRECISION MOTORS INC
838 WITTEN ROAD
BURLINGAME, CA 94010.
- SOURCE: SANDIA NATIONAL LABORATORY
DIVISION 1414.
- SOURCE: IMPERIAL EASTMAN
6300 W HOWARD ST
CHICAGO, IL 60648-1700.
- SOURCE: HELICAL
901 W MCCOYLANE
PO BOX 1089
SANTA MARIA, CA 93454.
- SOURCE: BIMBA MANUFACTURING
MONEE, IL 60449-0088.
- SOURCE: GORDON ARKANSAS INC
1000-T N SECOND ST
ROGERS, AR 72765.
- SOURCE: STERLING ELECTRONICS
3540-D PAN AMERICAN FRWY
ALB, NM 87107.
- SOURCE: MICRO SWITCH
DEPT 740
FREEPORT, IL 61032.
- SOURCE: PIC
PO BOX 1004
BENSON RD
MIDDLEBURY, CT 06762.
- SOURCE: ALLIED AMPHENOL PRODUCTS
BENDIX CONNECTOR OPERATIONS
40-80 DELAWARE ST
SIDNEY, NY 13838-1395.
- SOURCE: TRW ELECTRONIC COMPONENTS
GROUP CONNECTOR DIV
1501 MOTTE AVE
ELK GROVE VILLAGE, IL 60007-5282.
- SOURCE: KAYDON CORP
MUSKEGON, MI 49443.

Figure D-11. Assembly Drawing of the Dispenser Mechanism (Concluded)

A vector, $(A)_e$, represents the temporal position of the upper edge of the disk relative to a Newtonian reference frame, e , placed at the center of the carrier. The equation for $(A)_e$ is

$$(A)_e = l - e_1 + (r \cos \theta + t_p) e_2 \quad (1)$$

where

l - the distance from centerline to the edge of the disk (in.)
 r - the radius of the carrier (in.)
 t_p - the thickness of the disk or platchet (in.).

Similarly, a vector, $(B)_e$, represents the position of the lower edge of the disk, relative to the frame, e , of the carrier. The equation for $(B)_e$ is

$$(B)_e = l - e_1 + r \cos \theta e_2 \quad (2)$$

If a reference frame, u , is attached to the carrier such that as the carrier rotates, the reference frame rotates with it, then the position of the disk edges defined in the Newtonian frame, e , can be translated into the rotating frame, u . Such a transformation from the Newtonian reference frame to the rotating reference frame can be accomplished using a transformation matrix. A transformation matrix is used in engineering to translate coordinates of a vector in one frame of reference to another. The transformation matrix T_u^e will be used to transform the coordinates of the edges, $(A)_e$ and $(B)_e$, in frame e to corresponding coordinates, $(A)_u$ and $(B)_u$, in frame u . The equation representing T_u^e is shown below.

$$T_u^e = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \quad (3)$$

Thus, the equations for $(A)_u$ and $(B)_u$ are

$$(A)_u = T_u^e A_e \quad (4)$$

and

$$(B)_u = T_u^e B_e \quad (5)$$

or

$$(A)_u = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{Bmatrix} -l \\ r \cos \theta + t_p \end{Bmatrix} \quad (6)$$

$$(B)_u = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{Bmatrix} -l \\ r \cos \theta \end{Bmatrix} \quad (7)$$

The resulting equations are shown below.

$$(A)_u = (-l \cos \theta + r \sin \theta \cos \theta + t_p \sin \theta) u_1 + (l \sin \theta + r \cos^2 \theta + t_p \cos \theta) u_2 \quad (8)$$

$$(B)_u = (-l \cos \theta + r \sin \theta \cos \theta) u_1 + (l \sin \theta + r \cos^2 \theta) u_2 \quad (9)$$

$$(C) = r \cos \theta u_1 + r \sin \theta u_2 \quad (10)$$

Equation C is for the circle which describes the outer edge of the carrier. Note that this equation is not subscripted because it does not matter which reference frame is used to define the circle.

For the RRSAS project, the following values were chosen for the different variables:

- l = the distance from centerline to the edge of the plachet (0.200 in.)
- r = the radius of the plachet dispenser (0.4375 in.)
- t_p = the plachet thickness (0.135 in.).

The values of l and t_p have been increased to make room for plachet clearance as it passes through the mechanism, as well as to cover any differences in tolerances that build up during assembly. A computer-generated three-dimensional representation of the cam is given in Figure D-10.

MECHANISM ASSEMBLY DESCRIPTION

The assembly drawing of the complete plachet-dispensing mechanism is shown in Figure D-11. Each of the major components is discussed below.

TRANSMISSION

As shown in Figure D-11, a series of toothed pulley wheels (Item 38), along with the drive pulley belt (Item 39) and right angle gear drive (Item 40), transmit power to the individual carriers. An important factor observed in choosing belts and pulleys is the contact area between the belt and the pulleys. Pulley positions are selected to maximize contact between the belt and the pulleys to prevent slippage. To prevent drive motor overload, however, the area of contact between the belt and the pulley on the drive motor are kept to a minimum. Thus, if the mechanism jams during operation, the belt will slip on the motor-mounted pulley. This prevents the mechanism from becoming damaged, and keeps the individual dispensing cams synchronized during a jam. Maintaining cam synchronization reduces the downtime required to clear the mechanism.

The motor chosen for the system, Items 42 and 43 in Figure D-11, is oversized to prevent stalling if a small disturbance is encountered. With the stronger motor, small disturbances can be overcome while jamming can be handled with the overload protection scheme described above.

LOCKING MECHANISM

The locking mechanism locks the magazine onto the robot (Figures D-11 and D-12). Its design is a modification of that used on the Canberra machine, produced by Canberra Industries, Inc., Model 2405, which compensates for inaccurate robot movements. The robot merely places the magazine into the mechanism where it is locked into place.

The mechanism is a plate (Item 6) with pins (Item 28) attached to it, mounted in a bearing (Item 31) and actuated by a pneumatic piston (Items 48, 49, 50, 5, 12). A pilot tube (Item 29) helps the robot with magazine placement. A wedge-shaped stop (Item 1) inside the pilot tube prevents the magazine from rotating during the latching operation. Microswitches (Item 55) indicate whether the locking mechanism is locked or unlocked. A proximity sensor (Item 34) indicates the presence of the magazine within the pilot tube.

CONTROL

To monitor and control the system, various switches have been installed in the dispenser to enable the operator/computer to verify the mechanism's status. Mechanical switches (Items 22 and 55 in Figure D-12) are used to indicate whether the locking mechanism is open or closed, and a proximity switch (Item 34 in Figure D-12) indicates whether a magazine is in place. A photoelectric switch (Item 35 in Figure D-12) signals if a planchet has been successfully dropped. Another mechanical switch (Items 27 and 55 in Figure D-12) shuts down the robot if it strikes the mechanism. One final cam-operated switch (Items 54 and 57 in Figure D-11) keeps the mechanism in an operational mode until it reaches the end of its cycle. The sequence of events that occurs in mechanism operation is described in the following paragraphs.

At the beginning of any dispensing operation, several conditions must be verified by the system operator. One of the first items of interest involves verification of magazine placement: Is there a magazine of planchets placed in the mechanism? A proximity switch verifies the magazine's presence and allows the next step to be performed. If no magazine is detected, the supervising program alerts the operator of the status, and additional steps must be taken to remedy the situation.

The next condition checked is the status of the magazine lock. If a magazine is in place and is locked, a switch informs the system that it can proceed to the next step. If the magazine is not locked, then two states exist: either the operator intends to remove the magazine, or the magazine must be locked before the system can dispense a planchet.

The photoelectric switch is inspected before activating the dispenser. The photoelectric switch is used to verify the presence, or absence, of a planchet in the removal area of the mechanism. If a planchet is present, the robot can be instructed to remove the planchet for its own use. If, however, a planchet is not present, a start signal is transmitted to the dispenser.

A cam-operated switch powers the system during an operation cycle. An attached roller rides on a cam, which, in turn, resides on one of the dispenser shafts. When a start signal is received by the dispenser, a relay

D-15

powers the dispenser motor for the duration of the start signal, which is a 100-ms pulse. The motor rotates the mechanism to a point where the cam activates the mechanical switch, which, in turn, enables power to the motor. As long as the switch is engaged by the cam, the motor receives power. When the switch reaches the dwell section of the cam, it disconnects power to the motor, completing the dispenser cycle. A planchet will have been dispensed from the magazine, and the photoelectric switch will register its presence. The flow diagram shown in Figure D-13 illustrates this process.

MISCELLANEOUS ITEMS

Three important elements of the system also deserve mention. A flexible shaft coupling, Item 46 in Figure D-12, is used because exact shaft alignment is difficult to maintain. In addition, flexible shaft couplings add a small amount of compliance which reduces the damage potential to the mechanism in the event of a jam.

Another item of interest is the planchet retainer (Item 9 in Figure D-12). The retainer provides a storage buffer for the dispenser, eliminating the need for the robot to wait for a planchet, thereby increasing considerably the speed of the swiping process. The retainer is made of a thin film of polyethylene.

Figure D-13. Flow Diagram for Control of the Dispenser

REFERENCES

Thunborg, S., 1988. "A Robotic Radiation Survey and Analysis System," paper presented at Robots 12/Vision 88 Conference, sponsored by the Society of Manufacturing Engineers, Detroit, MI.

APPENDIX E

OSCILLATION-DAMPED MOVEMENT OF SUSPENDED OBJECTS*

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ABSTRACT

Transportation of an object using an overhead crane or manipulator can induce pendulum motion of the object. Residual oscillation from transportation typically must be damped or allowed to decay before the next process can take place. By properly programming the acceleration of the transporting device, e.g., crane, an oscillation-damped transport and swing-free stop are obtainable. This appendix reviews the theory and presents the mathematics associated with oscillation-damped trajectories for simply suspended objects using controlled acceleration, and describes a particular implementation using a CIMCORP XR® 6100 gantry robot.** In addition to the theoretical treatment, a specific hardware and software implementation currently in use at Sandia National Laboratories to generate oscillation-damped trajectories is discussed. Finally, sources of error resulting in small residual oscillations are identified and possible solutions presented.

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INTRODUCTION

Sandia National Laboratories (SNL) is currently investigating the feasibility of using intelligent machines at nuclear waste disposal sites. One class of operations necessary at a waste disposal site is transportation of nuclear waste shipping casks and other heavy objects to various locations throughout the installation. During overhead crane transportation, an object is free to swing. If any object oscillation begins, the oscillation must be damped by the operator, or the object must be allowed to swing until the amplitude decays sufficiently to allow the next operation to begin. Either situation results in reduced facility availability. However, damping the oscillation of simply suspended payloads during transportation is possible if the acceleration of the crane or manipulator is programmable.

MATHEMATICAL FOUNDATION

Figure E-1 is a simplified diagram of the transportation system under consideration. The transporting device moves in a horizontal direction that is normal to gravity, while the simply suspended payload is free to oscillate about the pivot point O. If the moving pivot point O undergoes a particular acceleration profile, the simply suspended payload will exhibit an oscillation-damped transport and a swing-free stop.

Figure E-2 shows one acceleration profile for the moving pivot point O that can result in an oscillation-damped trajectory for a simply suspended object. Point O has constant acceleration for time, t_a . After time t_a , point O moves at an intermediate constant velocity for time, T . At time, $t_a + T$, point O accelerates again with constant acceleration for time, t_a . T is selected such that the oscillation imposed on the object due to the second duration of acceleration is 180 degrees out of phase with initial oscillation of the swinging object, resulting in the object moving at constant velocity (during T_m) without oscillation. After an arbitrary length of time, T_m , applying the same procedure for deceleration results in a swing-free stop of the object. The objective is to determine the value of T , parameterized with respect to t_a , that yields oscillation-damped movement.

The motion of the swinging object can be described using the following differential equation (Karman and Biot, 1940; Tse et al., 1978; Thomson, 1981):

$$\ddot{\theta} + \omega_0^2 \sin\theta = 0 \quad (1)$$

where

θ - angular displacements

ω_0 - the natural frequency of oscillation.

Equation 1 is a second-order, nonlinear differential equation with constant coefficients. For small angles of oscillation, Equation 1 is typically linearized, therefore, greatly simplifying its solution. However, for large oscillation angles, a linear approximation of Equation 1 will not yield accurate results.

Figure E-1. Diagram of the Transportation System

Figure E-2. Acceleration Profile

Because large acceleration magnitudes of the transporting device will cause large oscillation angles of a simply suspended payload, the linear approximation to Equation 1 will not always be sufficiently accurate. Ideally, Equation 1 should be solved exactly. However, the exact solution to Equation 1 involves a complete elliptic integral of the first kind; hence, Equation 1 is insolvable in terms of elementary transcendental functions (Kaplan, 1952). Therefore, some method of accurately approximating Equation 1 for large oscillation angles becomes necessary.

Using a linear approximation and solving (1) for θ as a function of time yields (see Attachment A for details):

$$\theta = \alpha \sin \left[2\pi \frac{t}{\tau_0} \right] \quad (2)$$

where

α = amplitude of oscillation

τ_0 = period of the object for small amplitudes.

If Equation 2 is used for large oscillation amplitudes, significant error can result, as shown in Figure E-3. Figure E-3 shows angular displacement plotted as a function of normalized time for a swinging object. Notice the linear approximation in Equation 2 yields a sinusoidal curve similar to the exact numerical solution. However, the linear approximation period is significantly different from the exact solution. An approximate solution to Equation 1 that yields good results for large oscillation angles can be obtained by collecting all the nonlinearities into one parameter, the period (see Attachment A for details). Using the nonlinear approximation for the period of the swinging object and solving Equation 1 for θ as a function of time yields:

$$\theta = \alpha \sin \left[\frac{2\pi}{1 + (\alpha^2/16)} \left[\frac{t}{\tau_0} \right] \right] \quad (3)$$

The behavior of the nonlinear approximation, Equation 3, is close to that of the exact numerical solution shown in Figure E-3.

Figure E-4 shows the percent error in the calculated period using the linear and nonlinear approximations with respect to the exact solution as a function of maximum swing amplitude. The linear solution exceeds 1 percent error after approximately 20-degrees maximum amplitude. However, the nonlinear approximation exceeds 1 percent error only after 70-degrees maximum amplitude. Hence, if the system acceleration causes a maximum swing amplitude greater than a few degrees, the nonlinear aspects of the swinging object must be considered.

In theory, the analysis of the object's motion could continue to a maximum swing amplitude of 180 degrees before the transition from oscillatory to rotational motion occurs, and the analysis becomes invalid. However, in practice, the supporting member for simply suspended objects must always

Figure E-3. Angular Displacement vs. Normalized Time

Figure E-4. Error in Computed Pendulum Periods

remain in tension. At large swing amplitudes exceeding 90 degrees, the supporting member must go into compression to maintain oscillatory motion. Therefore, the practical upper limits of analysis for the remainder of this paper is 90-degrees maximum amplitude.

NUMERICAL RESULTS

Using the acceleration profile shown in Figure E-2 and the nonlinear approximation for the differential equation of motion (Equation 1), a function may be written that expresses the constant velocity time, T , as a function of acceleration time, t_a , and the nonlinear approximations for the period of the swinging object, τ_T and τ_{t_a} , which are functions of acceleration magnitude, a/g , and other measurable system parameters (see Attachment A for mathematical development):

$$T = \frac{\tau_T}{\pi} \tan^{-1} \left[\frac{\tau_T}{\tau_{t_a} \tan\left(\pi t_a / \tau_{t_a}\right)} \right] \quad (4)$$

where

- τ_T - the period of the swinging object, accounting for all nonlinearities during the time of intermediate constant velocity
- τ_{t_a} - the period of the swinging object, accounting for all nonlinearities during the time of constant acceleration.

Figure E-5 shows the surface defined by Equation 4 for intermediate constant velocity time, T , as a function of normalized acceleration, a/g , and acceleration time, t_a , for a swinging object with unit small angle period. Notice that the limits for acceleration time are zero and one-half. Zero acceleration time corresponds to impulse acceleration that results in an intermediate constant velocity time of one-half period, as demonstrated by Starr (1985).

An acceleration time of 0.5 corresponds to accelerating for one-half the small angle period of the swinging object, followed by an acceleration for another one-half period without an intermediate duration of constant velocity. This occurs if the magnitude of acceleration is infinitesimally small. Strip suggests this profile of acceleration time is equal to one-half the infinitesimally small angle period (Strip, 1986).

Notice the division on the surface of Figure E-5 between real (shaded section) and nonreal, or nonpractical, (unshaded section) solutions. Bounding the real solutions are two curves shown on the solution surface: the curve defining the intersection of the surface and the t_a , a/g plane, and the curve defining the boundary of nonpractical solutions.

The curve defining the intersection of the surface and the t_a , a/g plane separates real from nonreal solutions. If a solution lies below the t_a , a/g plane, the required constant velocity time has a negative value. Because

Figure E-5. Surface Defining Nonlinear Approximation

negative time is not a real solution, any part of the surface extending below the t_a , a/g plane is ignored.

The curve shown in Figure E-5 as the boundary of 90-degrees maximum amplitude defines the limit of maximum swing amplitude. If the angular displacement and velocity at time, t_a , are such that the swinging object has a maximum swing amplitude greater than 90 degrees during the intermediate constant velocity, it is not a practical solution. Furthermore, the characteristics of the actual system may reduce the practical limit of maximum swing amplitude to less than 90 degrees.

Figure E-6 shows a surface similar to that in Figure E-5, except Figure E-6 assumes a linear approximation for motion of the swinging object, while Figure E-5 uses the nonlinear approximation for the motion of the swinging object. Notice both approximations approach the same true linear solution as acceleration approaches zero.

However, as acceleration increases, the two surfaces show a significantly different behavior. The surface for the linear approximation tends to bend up, indicating that the duration of constant velocity, T , increases as the system's acceleration magnitude, a/g , increases. In contrast, the surface for the nonlinear approximation (Figure E-5) tends to curve down toward reduced constant velocity time as acceleration magnitude increases.

Note that if the desired working region is in the area of increased acceleration magnitude, the nonlinear characteristics of the swinging object

Figure E-6. Surface Defining Linear Approximation

must be included. In fact, if the working region is in the area of large acceleration magnitude and time, it is more accurate to neglect the effects of acceleration and assume a linear approximation for the motion of the simply suspended object than to include the effects of acceleration and assume a linear approximation.

IMPLEMENTATION

Hardware

Figure E-7 shows the implementation for an oscillation-damped control strategy on a CIMCORP XR[®] 6100 robot at SNL. A desired displacement is entered into the control computer, which then generates the required robot acceleration profile needed to develop oscillation-damped trajectory for a simply suspended object. This acceleration profile is sent to the standard CIMROC[®]* 2 robot controller through a CIMCORP line tracker board in the form of robot position updates every 47 ms. The standard robot controller determines the robot trajectory required to achieve this new position and sends the results into the robot servo control loop.

Software

The software in the control computer provides both low-level interrupt-driven communications and high-level trajectory computation.

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Figure E-7. Implemented Control Strategy

The communication between the robot controller and the control computer is synchronized by the robot controller through the line tracker board. The board sends a synchronizing pulse to the control computer every 47 ms. When the control computer receives the synchronizing pulse, it interrupts the currently active trajectory computation routine and sends the most current position update over a serial communication line to the line tracker board. After sending the position update to the line tracker board, the communication routine running on the control computer returns control to the trajectory computation routine.

The trajectory computation routine calculates the required position updates to obtain an oscillation-damped trajectory by essentially selecting a point on the surface (Figure E-5) that satisfies the condition of desired displacement. After a desired displacement is entered into the trajectory computation routine, the routine assumes an acceleration time, t_a , and a corresponding intermediate constant velocity time, T , thereby selecting a particular contour line on the surface, shown in Figure E-5. The trajectory computation routine then iterates a solution between acceleration magnitude, a , and maximum constant velocity time, T_m , using Equation 2, and the following equation for total displacement of point 0:

$$S = 4 a t_a^2 + 2 a t_a T + 2 a t_a T_m \quad (5)$$

where

S = total displacement for point 0.

After all parameters are determined, the trajectory computation routine calculates the oscillation-damped trajectory position updates, based on the 47-ms update rate of the line tracker board.

To move the robot, the trajectory computation routine passes a position update to the communication routine. The communication routine blocks execution of the trajectory computation routine until it receives a synchronization pulse from the line tracker board, thereby properly synchronizing the trajectory computation routine with the line tracker board. When the communication routine senses the synchronization pulse, it transmits the next position update to the line tracker board, then returns control to the trajectory computation routine. This process continues until the desired trajectory is complete.

RESULTS

To test the above control strategy, a 50-lb weight was suspended by an 80-in. cable from the XR[®] 6100 robot gripper. The small angle period of the pendulum was measured to be 2.87 s.

The results of a sample test are given in Table E-1. During this test, the acceleration of the pivot point, or robot gripper, remains constant for all trials at 12 in./s² in a horizontal direction. Likewise, the total robot displacement holds constant at 100 in.

Concerning the residual oscillation shown in Table E-1, no residual oscillation in theory should occur after the robot has come to rest. In practice, deviations from theory resulting in residual oscillation stem from many sources. Based on computer simulations of this control strategy, the largest source of error results from the update rate of the digital control system. For the system described above, the position update rate is approximately 47 ms; therefore, if the desired acceleration profile is not precisely definable in 47-ms intervals, some residual oscillation will result. Another source of error results from time delays due to the response of the mechanical subsystem. Any deviation in implementation from the desired acceleration profile can result in a distorted acceleration profile and, hence, residual oscillation. Also, the servo control loop itself can induce error. The servo loop requires a position error to output power to the servo motors on the manipulator (Figure E-7). Therefore, the manipulator's actual position is always a nonconstant distance behind the desired position, resulting in a distorted acceleration profile. Finally, any initial oscillation of the swinging object will, in general, result in residual oscillation.

As a comparison to the approach of generating constant acceleration profiles, a test was conducted wherein the standard CIMROC[®] 2 robot controller governed the acceleration profile of the robot gripper using a cubic spline trajectory (Sturm, 1983). The maximum acceleration was set to 12 in./s², and the maximum velocity, to 15 in./s. For a 100-in. move, the resulting residual oscillation was 8.7 degrees. Residual oscillation of 8.7 degrees is significantly greater than the residual oscillation for the oscillation-damped

Table E-1
Results for Implemented System

t_a (s)	T (s)	T_m (s)	V_{max} (in./s)	Residual Oscillation (degrees)
1.44	0.000*	0.0336	34.4	0.1
1.15	0.287	1.05	27.6	0.3
0.861	0.574	2.54	20.7	0.3
0.574	0.841	5.25	13.8	0.1
0.287	1.15	12.8	6.89	0.1

* closest real solution

trajectories shown in Table E-1. Therefore, the proposed constant acceleration control strategy will, in general, yield a better oscillation-damped trajectory than possible with the CIMROC® 2 controller.

CONCLUSIONS

While experimenting with the computer simulation and implemented control system, several practical observations have been made.

1. As the acceleration of the pivot point approaches zero, the equations of motion describing the swinging object approach linear behavior; hence, the equations that generate the oscillation-damped trajectory may be greatly simplified by making linear approximations for the motion of the swinging object:

$$\ddot{\theta} + \omega_o^2 \theta = 0 \quad (6)$$

2. The implemented system will always deviate from the exact solution, resulting in residual oscillation of the payload due to the nonidealities in the control and mechanical systems. These nonidealities include the finite update rate of the controller, response delays in the mechanical system, and response delays in the servo loop. In general, all these nonidealities are characteristics of the particular system used. Therefore, care must be taken when selecting or designing a system to generate oscillation-damped trajectories to ensure that it behaves as close to ideally as possible.
3. Residual oscillation can also result from an initial oscillation of the payload. In general, the oscillation-damped trajectory will not decrease this initial movement. Moreover, the oscillation-damped trajectory may amplify the initial oscillation.

4. From the above observations, it is obvious that an oscillation-damped trajectory with zero residual oscillation may be difficult to implement in some cases. SNL is currently developing a hybrid force-control system to damp residual oscillation of simply suspended payloads by controlling the dynamic forces created by the swinging payload (Strip, 1986).
5. One drawback of generating oscillation-damped trajectories as presented in this appendix is the necessity of a system able to produce a constant acceleration profile. Many commercially available programmable cranes and manipulators do not have the ability to generate a constant acceleration profile. However, many acceleration profiles can result in an oscillation-damped trajectory by applying the proper mathematical conditions (Strip, 1986).

REFERENCES

Kaplan, W., 1952. *Advanced Calculus*, Reading, MA: Addison-Wesley.

Karman and Biot, 1940. *Mathematical Methods in Engineering*, New York: McGraw-Hill.

Starr, G. P., 1985. "Swing-Free Transport of Suspended Objects with a Path-Controlled Robot Manipulator," *Journal of Dynamic Systems, Measurement and Control*, 101:97-100

Strip, D. R., 1986. "Swing-Free Transport of Suspended Objects: A General Treatment," SAND87-0714, Sandia National Laboratories, Albuquerque, NM.

Sturm, A. J., 1983. "Robotic Trajectory Control of Acceleration and Velocity Using Cubic Splines," presented at the 8th Applied Mechanisms Conference, St. Louis, MO.

Thomson, W., 1981. *Theory of Vibrations with Applications*, New Jersey: Prentice-Hall.

Tse, F., H. E. Morse, and R. T. Hinkle et al., 1978. *Mechanical Vibrations Theory and Applications*, Boston: Allyn and Bacon.

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ATTACHMENT A TO APPENDIX E

DYNAMIC ANALYSIS OF A SWINGING BODY

Figure E-8 shows a free-body diagram of a distributed mass with a moving pivot point where

- O - moving pivot point for the mass
- G - center of mass for the object
- m - mass of the object
- l - length from O to G
- J - mass movement of inertia about O
- g - the gravitational acceleration (along y)
- a - acceleration of point O (normal to y)
- θ - angular displacement of the object from y
- θ' - angular displacement of the object from y'.

Figure E-8. Simply Suspended Object

The object can pivot at O and oscillate freely about y of the xy coordinate frame while point O is stationary or moving with constant velocity. A second axis, y' of the x'y' coordinate frame, is the axis about which the object oscillates while point O is moving with constant acceleration. Using this second coordinate frame allows the use of standard relations to analyze the motion of the object. A simple coordinate transformation relates the two coordinate frames.

A dynamic analysis of the object yields the following nonlinear differential equation of motion that is valid while point O is stationary or moving with constant velocity (Karman and Biot, 1940; Tse et al., 1978; Thomson, 1981).

$$\ddot{\theta} + \omega_o^2 \sin\theta = 0 \quad (A-1)$$

where the natural frequency of the object is

$$\omega_o = \left[\frac{m l g}{J} \right]^{1/2} \quad (A-2)$$

While point O is moving with constant acceleration, the natural frequency changes due to a change in the magnitude of the effective acceleration vector; hence, the new natural frequency becomes

$$\omega_o = \left[\frac{m l [a^2 + g^2]^{1/2}}{J} \right]^{1/2} \quad (A-3)$$

The assumption is now made and verified below that a new natural frequency exists that approximates all the nonlinearities in the differential equation describing the motion of the swinging object. Equation A-1 then becomes

$$\ddot{\theta} + \omega^2 \theta = 0 \quad (A-4)$$

where

ω = natural frequency, accounting for all nonlinearities.

Equation A-4 is a second-order, linear differential equation with constant coefficients and is solvable using Laplace transforms. After transforming Equation A-4, solving for the subsidiary equation, and then transforming back into the time domain, the solution for angular displacement with respect to time becomes

$$\theta(t) = \theta_1 \cos(\omega t) + [\dot{\theta}_1 / \omega] \sin(\omega t) \quad (A-5)$$

where

θ_i - initial angular displacement
 $\dot{\theta}_i$ - initial angular velocity
 t - time.

Differentiating with respect to time yields angular velocity with respect to time:

$$\dot{\theta}(t) = -\theta_i \omega \sin(\omega t) + \dot{\theta}_i \cos(\omega t) \quad (A-6)$$

Oscillation-Damped Trajectories

The problem now is solving for the constant velocity time, T , in terms of acceleration time, t_a , and other system parameters. Assuming the two durations of constant acceleration are equal in time, t_a , and magnitude, a , the following conditions will result in an oscillation-damped transport and stop of the object (Starr, 1985).

$$\theta(t_a) = \theta(t_a + T) = \theta \quad (A-7)$$

$$\dot{\theta}(t_a) = -\dot{\theta}(t_a + T) = \dot{\theta} \quad (A-8)$$

Substituting conditions in Equations A-7 and A-8 into Equations A-5 and A-6 gives

$$\theta = \theta \cos(\omega_T T) + [\dot{\theta}/\omega_T] \sin(\omega_T T) \quad (A-9)$$

$$-\dot{\theta} = -\theta \omega_T \sin(\omega_T T) + \dot{\theta} \cos(\omega_T T) \quad (A-10)$$

where

ω_T - natural frequency of the swinging object, accounting for all nonlinearities during the intermediate constant velocity.

Solving Equation A-9 for $\sin(\omega_T T)$, substituting the result into Equation A-10, and using a tangent half angle substitution yields:

$$\tan \left(\frac{\omega_T T}{2} \right) = \frac{\dot{\theta}}{\omega_T \theta} \quad (A-11)$$

which is valid for

$$\theta \cdot \dot{\theta} \geq 0 \quad (A-12)$$

where

θ - angular displacement in the xy coordinate frame at time t_a

$\dot{\theta}$ - angular velocity at time t_a .

Using Equations A-5 and A-6 to obtain θ and $\dot{\theta}$ at time t_a in the x'y' coordinate frame, transforming θ and $\dot{\theta}$ to the xy coordinate frame, and substituting into Equations A-11 yields

$$T = \frac{\tau_T}{\pi} \tan^{-1} \left[\frac{\tau_T}{\tau_{t_a} \tan(\pi t_a / \tau_{t_a})} \right] \quad (A-13)$$

where

τ_T - the period of the swinging object, accounting for all nonlinearities during the time of intermediate constant velocity

τ_{t_a} - the period of the swinging object, accounting for all nonlinearities during the time of constant acceleration.

Equation A-13 relates the duration of the intermediate constant velocity segment, T , to the duration of a constant acceleration segment, t_a , as a function of the nonlinear approximations for the period of each segment. Now the nonlinear approximations for the period of each segment need to be expressed in terms of determinable system parameters.

Nonlinear Approximation for Period

One way of dealing with the nonlinear motion of a swinging object is to combine all the nonlinearities into one parameter, the exact period. Karman and Biot approximate the exact period as (Karman and Biot, 1940)

$$\tau = 2\pi \left[\frac{J}{m l g} \right]^{1/2} \left[1 + \frac{\alpha^2}{16} \right] \quad (A-14)$$

where

α - maximum angular amplitude of the swinging object.

Using Equations A-3 and A-14, the nonlinear approximation for the period of the object while the moving pivot point O is accelerating becomes

$$\tau = 2\pi \left[\frac{J}{m l [a^2 + g^2]^{1/2}} \right]^{1/2} \left[1 + \frac{\alpha^2}{16} \right] \quad (A-15)$$

While point O is accelerating at a constant rate, α is the angle between the xy and x'y' coordinate systems. Hence, Equation A-15 can be expressed entirely in terms of determinable system parameters [see Strip (1986) for expanded derivation]:

$$\tau_{t_a} = \tau_o \left[\frac{1}{[1 + (a/g)^2]^{1/2}} \right]^{1/2} \left[1 + \frac{[\tan^{-1}(a/g)]^2}{16} \right] \quad (A-16)$$

where

τ_o - the period for an infinitesimally small angle of oscillation while point O is moving with constant velocity.

Using Equation A-14 to solve for the period of an object while point O is moving with constant velocity and expressing the maximum amplitude as a function of conditions at time, t_a , yields:

$$\frac{2\pi}{\tau_o} = \frac{2\pi}{\tau_T} \left[1 + \frac{\theta^2 + (2\pi\dot{\theta}/\tau_T)^2}{16} \right] \quad (A-17)$$

Solving this nonlinear approximation for the period while point O is moving with constant velocity results in the quadratic equation

$$\frac{2\pi}{\tau_T} = \frac{2\pi/\tau_o \pm \left[(2\pi/\tau_o)^2 - 4(1 + \theta^2/16)(\dot{\theta}^2/16) \right]^{1/2}}{2(1 + \theta^2/16)} \quad (A-18)$$

As the angular displacement and velocity approach zero, the nonlinear approximation for the period should approach that of the small angle period. Therefore, the proper choice is the positive radical of Equation A-18. Hence, the nonlinear approximation for the period of the object during the time of intermediate constant velocity becomes

$$\tau_T = \frac{2\pi(1 + \theta^2/16)}{\pi/\tau_o + \left[(\pi/\tau_o)^2 - (1 + \theta^2/16)(\dot{\theta}^2/16) \right]^{1/2}} \quad (A-19)$$

Substituting Equations A-16 and A-19, along with angular displacement and velocity at time, t_a , in the xy coordinate frame, into Equations A-13 yields a solution for the duration of constant velocity, T, in terms of acceleration time, t_a , for an oscillation-damped trajectory.

Error Analysis

Comparing the solutions to the linear and nonlinear approximations, an exact solution for the motion of a swinging object demonstrates the necessity and validity of combining all nonlinearities into an approximate period. Using Equations A-5, with the initial conditions of zero angular displacement and maximum angular velocity, the angular displacement as a function of time for the linear approximation is

$$\theta = \alpha \sin \left(2\pi \frac{t}{\tau_o} \right) \quad (A-20)$$

Using Equations A-14 for the nonlinear approximation of the period of a swinging object and substituting this approximation for the period into Equations A-20 gives the nonlinear approximation for angular displacement as a function of time:

$$\theta = \alpha \sin \left[\frac{2\pi}{1 + (\alpha^2/16)} \left[\frac{t}{\tau_0} \right] \right] \quad (A-21)$$

The exact solution for angular displacement as a function of time for the swinging object with the same initial conditions as Equations A-20 and A-21 is (Karman and Biot, 1940)

$$\sin \left(\frac{\theta}{2} \right) = \sin \left(\frac{\alpha}{2} \right) \operatorname{sn} \left(2\pi \frac{t}{\tau} \right) \quad (A-22)$$

where

sn = is a Jacobi elliptic function
 τ = is the exact period.

Solving Equation A-22 for angular displacement and expanding the elliptic function yields

$$\theta = 2 \sin^{-1} \left[\sin \left(\frac{\alpha}{2} \right) \sin \left(2\pi \frac{\tau_0}{\tau} \frac{t}{\tau_0} \right) \right] \quad (A-23)$$

where the ratio of the exact period to the period for an infinitesimally small angle of oscillation is (Karman and Biot, 1940)

$$\frac{\tau}{\tau_0} = \frac{2}{\pi} \left[\int_0^{\pi/2} \frac{d\psi}{\left[1 - \sin^2(\alpha/2) \sin^2(\psi) \right]^{1/2}} \right] \quad (A-24)$$

Equation A-24 is in the form of a complete elliptic integral of the first kind and is insolvable in terms of elementary transcendental functions (Karman and Biot, 1940). However, a numerical solution for Equation A-24 is possible for a given amplitude.

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