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ABSTRACT

A mobile robot system called the Stored Waste Autonomous Mobile Inspector (SWAMI) is under development by the Savannah River Technology Center (SRTC) Robotics Group of Westinghouse Savannah River Company (WSRC) to perform mandated inspections of waste drums stored in warehouse facilities. The system will reduce personnel exposure to potential hazards and create accurate, high-quality documentation to ensure regulatory compliance and enhance waste management operations. Development work is coordinated among several Department of Energy (DOE), academic, and commercial entities in accordance with DOE's technology transfer initiative. The prototype system, SWAMI I, was demonstrated at Savannah River Site (SRS) in November, 1993. SWAMI II is now under development for field trials at the Fernald site.

INTRODUCTION

Thousands of drums of radioactive, hazardous, and mixed waste are currently stored at DOE sites throughout the United States. These drums are stored in warehouse-like facilities on an interim basis, pending final disposition. Recent emphasis on anticipated decommissioning of facilities indicates that many more drums of waste will be generated, requiring additional storage. Federal and state regulations dictate that hazardous waste covered by the Resource Conservation and Recovery Act (RCRA) be inspected periodically for container degradation and to verify inventories. All known DOE waste storage facilities are currently inspected manually. A system to perform robotic inspection of waste drums is under development by the SRTC Robotics Group of WSRC. The robotic system is the Stored Waste Autonomous Mobile Inspector (SWAMI).

The DOE Office of Technology Development (OTD) is directing this effort through the Robotics Technology Development Program (RTDP) and through Morgantown Energy Technical Center (METC). In accordance with DOE's technology transfer initiative, development work is coordinated among several DOE, academic, and commercial entities. Along with WSRC, participants include the Lawrence Livermore National Laboratory (LLNL), the University of Michigan, the University of South Carolina, the Georgia Institute of Technology, Martin Marietta Astronautics Division, and Fernald Environmental Restoration Management Corporation (FERMCO).

OBJECTIVES AND BENEFITS

Program objectives fall into several categories: reducing personnel hazards, increasing cost effectiveness, improving inspection data quality, and providing additional information to enhance waste management operations.

Manual inspections of waste drums require personnel to be in close proximity to waste materials for extended periods of time, creating a potential for exposure to hazardous or radioactive materials. Robotic inspections will drastically reduce personnel exposure to these hazards. Significant cost savings can also be realized by reducing the personnel time required for inspections.

Since facilities of this type are typically capable of storing thousands of waste drums at a time, manual inspection is extremely tedious, and significant variations in inspection quality can be expected. Additional inconsistencies are introduced by the variations in the competence and experience level of inspectors. Robotic inspection of waste containers will not exhibit the degradation of quality or the variability associated with human performance in highly repetitive tasks. High-quality, consistent inspection data will contribute directly to prevention of waste containment failures. The vehicle's sensor mast will also allow SWAMI to inspect the topmost level of drums (up to four drums high) as competently as the first level, a feat not easily achieved with manual inspections.

SWAMI also provides additional information not currently available with manual inspections. During the inspection, SWAMI will store images of each drum and data associated with it, including geometric data, the drum's location, bar code number, and a time stamp. After downloading, this information can be accessed directly through the site database for inventory verification, drum condition trending and other operations support. SWAMI will also conduct a rigorous survey of the facility floor for potential radioactive contamination. Performing a radiation survey during every inspection serves two functions: it provides an early alert to a radioactive spill, and also prevents the vehicle from unwittingly picking up the contamination and tracking it throughout the facility, as might conceivably occur during a manual inspection.

PROGRAM

The project is divided into four phases: prototype development and demonstration (SWAMI I), system development (SWAMI II), demonstration and testing of SWAMI II at Fernald, and transfer of technology to industry. Prototype development was initiated in 1992 and culminated in a series of SWAMI I demonstrations during the RTDP Robotics for Mixed Waste Operations Demonstration at Savannah River Site in November 1993 (See Fig. 1.). SWAMI II is currently being developed, and will incorporate lessons learned during prototype development, include several features not found on SWAMI I, and address Fernald-specific requirements. SWAMI II is currently scheduled to begin approximately 17 weeks of field demonstrations and testing at Fernald in June of 1995. Following the demonstration, an offering of SWAMI II technology will be made to industry through the SRS Technology Transfer Department.

Since technology transfer to industry is a fundamental program objective, developing a system that performs its function in a cost-effective manner is of major import. Development strategy is to utilize known commercial technologies, then apply and integrate them in an innovative way. Vehicle subsystems are being developed independently and then integrated on the vehicle platform. This modularization of subsystems is also reflected in the system software.

PROJECT CONSTRAINTS

Although the parameters used for developing the vehicle are a composite of the general features of existing and planned storage facilities at the target sites, SWAMI II will initially be deployed at the Fernald Site for testing and demonstrations. As a result, Fernald waste storage specifications are predominately being used to configure SWAMI II. Waste storage facilities at Fernald are a combination of previously existing process facilities and dedicated storage facilities. Although other containers are present in relatively small numbers, SWAMI II will be targeted to inspect 55- and 85-gallon drums. These containers are stacked on pallets up to four levels high. Each drum is bar coded with a unique number for identification. Bar code label placement is relatively uniform. Aisles are a minimum of 0.91 m (36 in.) wide, many of which allow vehicle access from only one end, requiring

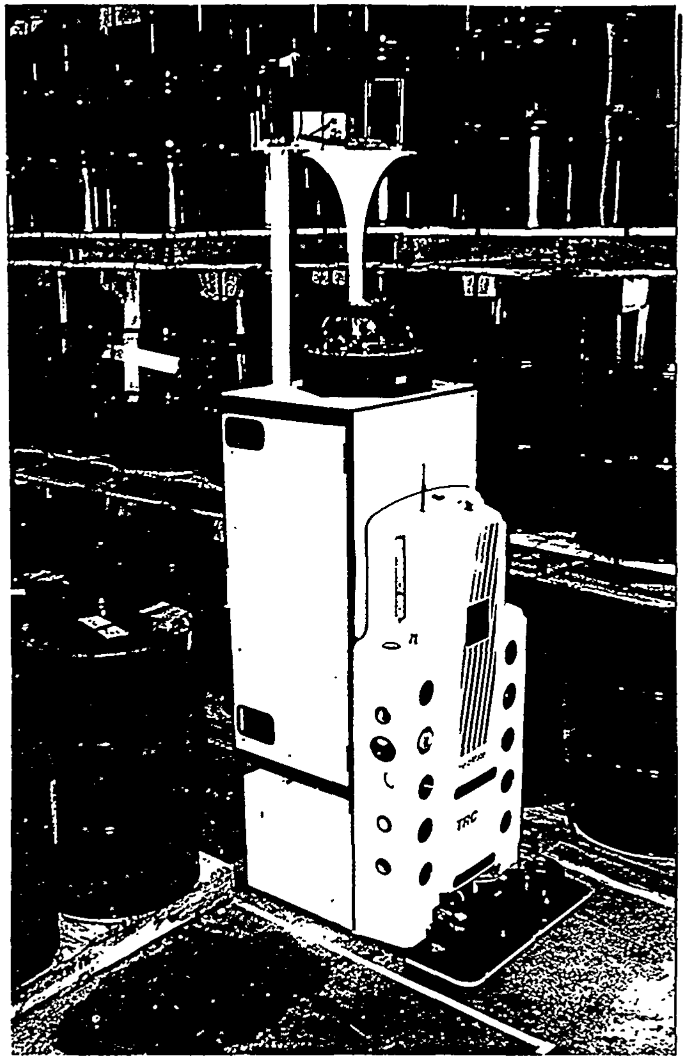

Fig. 1. SWAMI I at the November, 1993 RTDP Robotics for Mixed Waste Operations Demonstration.

Note: SRS # 93-1978-6 Already approved for offsite release

SWAMI II to back out of aisles. Storage facilities typically do not have temperature control. Several storage facilities have a drum capacity of approximately 12,000 drums.

SWAMI I DESCRIPTION

The SWAMI I systems fall into four general groups: the operator computer, the vehicle supervisory computer, the base vehicle, and vehicle subsystems. There are four main vehicle subsystems: image capture/compression/storage, bar code scanners, the radiation monitor, and the position determination system.

Operator Computer

The operator computer uses two programs to interact with SWAMI I: the SWAMI Operator Interface and RADMAP. Both were developed by SRTC. The SWAMI Operator Interface provides remote vehicle controls, an inspection interface, and a configuration interface. RADMAP provides a facility map on the operator screen with the vehicle's current position and status indicated with an icon. Radiation data can also be plotted as it is received from SWAMI I, or at a later time. Other information, such as alarms, can also be displayed.

RADMAP has been submitted for copyright by SRTC and will be available for technology transfer. The operator computer communicates with the vehicle supervisory computer over a spread spectrum radio ethernet.

Vehicle Supervisory Computer

The vehicle supervisory computer consists of three microcomputers on a half-height VME backplane and other peripherals, including a LAN board, and digital and serial interfaces. It communicates with the operator computer over a spread-spectrum radio ethernet, and commands the base vehicle and onboard subsystems through RS-232 and RS-485 (multidrop) serial ports. The vehicle supervisory computer software was developed by the University of South Carolina. SWAMI I is the first commercial mobile robot to utilize GENeral Interface for Supervisor And Subsystems (GENISAS) software from the Generic Intelligent System Control (GISC) library created by the OTD Robotics Program. "GENISAS is a GISC-Kit package that provides general communication software interface capabilities (such as command processing and event handling) between the supervisory control system and subsystems."[1]

Base Vehicle

The base vehicle is a modified Transitions Research Corporation (TRC) HelpMate®. Several modifications, such as pallet-sensing ultrasound transducers and vehicle software enhancements, were added by TRC. Other modifications were made by SRTC, including the addition and integration of subsystems. The vehicle is equipped with several systems to perform navigation, collision avoidance and collision recovery. Basic navigation is performed by dead reckoning, using encoders on the drive wheels and a gyroscope. An ultrasonic array faces forward and to each side of the vehicle. These sensors register physical features and update navigation. Collision avoidance is also accomplished using these sensors. Additional ultrasound transducer "blossoms" are mounted on the front bumper to register off of drum pallets. A forward-looking structured light system provides additional collision avoidance capability. Should a collision occur, pressure-sensitive strips located around the vehicle's periphery and compliant bumpers with deflection sensors are used to detect the impact location to aid in recovery. Emergency stop switches are also provided. The vehicle's 0.71 m (28 in.) overall width will allow it to successfully navigate within the 0.91 m (36 in.) wide aisles at Fernald.

Image Capture/Compression/Storage

The SWAMI I image capture/compression/storage system uses fixed-mount CCD color video cameras and light strobes for each drum level and aisle side. The strobes provide consistent lighting levels for image capture while minimizing power consumption. A PC-DOS (486/33 MHz) computer performs the actual image collection functions. At a command from the vehicle supervisory computer, the image system captures the digital drum images, compresses them, and attaches other data to the compressed file, including each drum's bar code number, drum location and a time stamp. The entire file is then stored to an onboard optical disk. Image capture and compression functions are performed on commercially available PC-DOS boards.

Bar Code Scanners

Fixed-mount rastering bar code scanners read the unique bar code number on each drum. A separate scanner is used for each drum level and aisle side. The scanners use a 670 nm visible laser diode light source, which is eye-safe. Since the bar codes are oriented "picket fence" style, the laser scans horizontally. A raster feature indexes the horizontal laser line vertically, creating a "scan window." This window allows the scanner to read bar codes whose location and orientation are not precisely controlled. The simple raster feature avoids the complexity, expense, weight, and power requirements of omnidirectional units. The scanners collectively communicate with the vehicle supervisory computer through a single RS-485 multidrop port.

Radiation Monitor

The radiation subsystem monitors the floor for potential alpha and beta-gamma radioactive contamination as SWAMI I performs its inspection. The system uses gas proportional detectors, located in front of the vehicle, to detect contamination before the vehicle passes over it. Onboard P-10 gas cylinders are required to continuously purge the detectors. The system is the same as that used on SIMON, another SRTC mobile robot. SIMON has demonstrated that robotic surveys are superior to manual surveys in detecting low levels of radioactive contamination. As SWAMI I performs the inspection, data from the radiation subsystem is sent to the operator interface computer in real time over the radio ethernet and displayed on RADMAP.

Position Determination

Due to the large area SWAMI I must navigate within, accumulated errors in the base vehicle's dead reckoning navigation system will become significant. The position determination subsystem updates the vehicle's dead-reckoned position and maintains the vehicle's odometry within acceptable accuracy. Accuracy is required not only for vehicle navigation, but also so that drum images are taken from the proper vehicle position. The system uses a 360-degree scanning laser to read bar coded retroreflective fiducials placed on the facility walls. This information is then used to periodically refine the HelpMate's dead-reckoned position.

SWAMI II DEVELOPMENT

The SWAMI II system to be tested at Fernald will utilize the same base vehicle as SWAMI I, but will differ in several aspects from the prototype already demonstrated. Additional subsystems will enhance SWAMI II's ability to perform a comprehensive inspection and reduce the operator workload. Several changes are also being made to address Fernald's specific site requirements.

Geometric Inspection

A significant addition to SWAMI II will be a geometric inspection subsystem, which uses structured light to detect drum dents and blisters. Since the storage facilities at Fernald typically experience significant turnover, damage to drums (such as dents) from handling operations can occur. Another potential failure mode is corrosion of drums from the inside. This type of failure is difficult to detect visually, until it is manifested by a blister on the drum's exterior. The geometric inspection system will detect these blisters to identify an imminent containment failure. It utilizes two arrays of laser line generators and CCD cameras to obtain range-to-surface data.

Waste storage drums at Fernald are painted glossy black, a surface which makes geometric inspection with structured light difficult. Structured light systems rely on a diffuse reflection of the laser line for detection by the camera. The curved glossy black drum surfaces absorb some of the light, and reflect most of the remaining light specularly. As a consequence, very little of the impinging laser light is visible to the imaging cameras. To obtain an adequate return from the projected laser line under these conditions (while remaining in the Class II eyesafe laser realm), the orientation, laser intensity and standoff distance of the sensor package must be maintained as the sensor passes each drum.

In order to provide the required geometry, inspection platforms will be built so as to position two arrays of laser line projectors to generate two contiguous horizontal laser lines on the drum (See Fig. 2.). Two laser lines are required to fully inspect each drum's visible surface, since the cameras' view of each laser line will be periodically blocked at the top or bottom of each drum. An interlaced array of CCD cameras will sequentially capture the laser line image as the inspection array moves vertically, parallel to the drum axis. Data from the geometric inspection will be transmitted to the operator computer during the inspection mission for subsequent computer analysis.

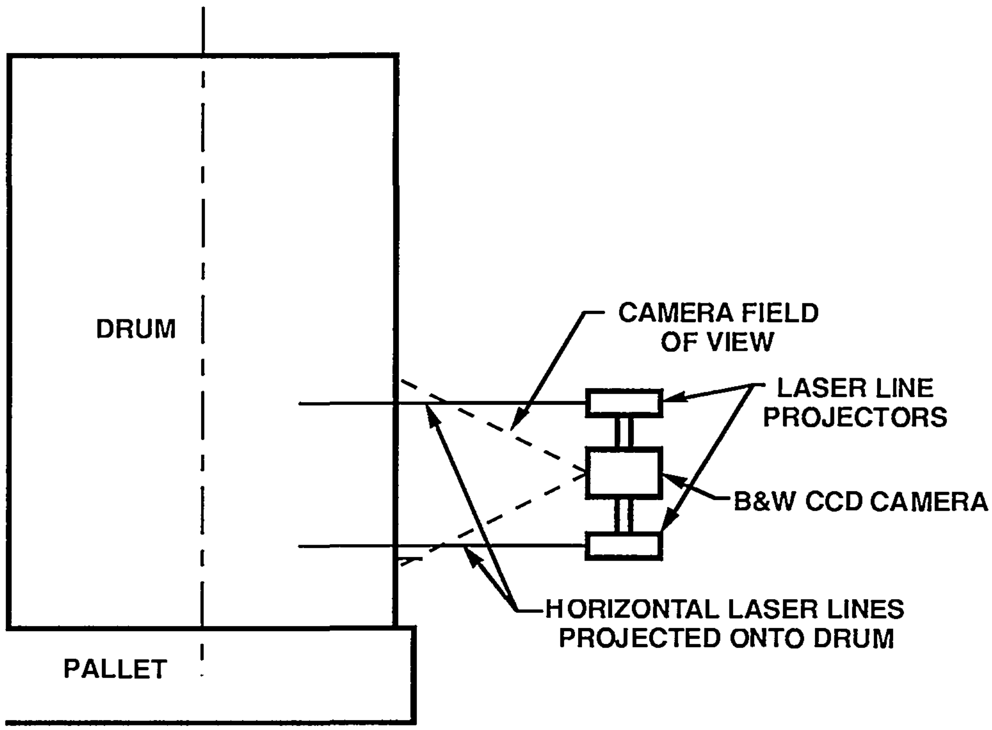

Fig. 2. Geometric Inspection Platform

Drum Locating

Since the structured light system requires its lasers and cameras to be aimed accurately relative to the drum axis, a drum locating subsystem will use ultrasound sensors to locate each drum during the inspection. One pair of ultrasounds mounted on the vehicle will locate the bottommost drum to position the vehicle for inspection of a drum column. As the inspection array moves vertically and transitions to subsequent drum levels in the column, another set of sensors mounted on the inspection array will provide drum location information so that variations in drum location within the column can be accommodated.

Rust Spot/Streak Analysis

As drums are inspected, SWAMI II will also capture and transmit color drum images to the operator computer. In order to achieve the required resolution, each drum will require several piecemeal images to be taken. The operator computer will then perform an image analysis for rust spots and streaks, and will present only those drum images which indicate a potentially unacceptable corrosion condition to the operator. Drum images and associated data will be archived in a mass storage medium accessible to the operator and other site organizations. A prototype for the rust analysis system was developed by Martin Marietta

Astronautics. Lawrence Livermore National Laboratory is developing the rust analysis subsystem for SWAMI II.

Site Database Interface

Fernald is implementing a Sitewide Waste Information Forecasting and Tracking System (SWIFTS). SWAMI II will interface with SWIFTS to obtain current information on the waste container inventory in the facility to be inspected, including each container's size and location within the facility. After an inspection, SWAMI II will report back to the database any discrepancies between the expected and discovered inventory. Drum images, geometric inspection data and other SWAMI II file data can also be accessed via the SWAMI II database.

Autonomous Backing

Since many of Fernald's aisles allow vehicle access from only one end, the base vehicle will be modified to allow autonomous backing with sensors to prevent collisions. Although the HelpMate is capable of backing to recover from a collision, its path planning software does not accommodate following a path while backing. Furthermore, the HelpMate's sensor array is configured for forward motion. The University of Michigan is developing an independent ultrasound subsystem which will use its own sensor array to navigate and control the base vehicle drive system during backing. It will also detect objects in its path to prevent collisions.

Scintillation Type Radiation Monitor

Scintillation-type radiation detectors are being implemented for SWAMI II. SWAMI I uses gas proportional detectors, which must be purged with P-10 gas before and during operation. Scintillation detectors do not require P-10 gas, so the onboard space requirements and mass of gas cylinders are eliminated. Lengthy preinspection purge times and gas management equipment are also eliminated. The computer and detector system is being developed by National Nuclear Corporation (NNC).

Position Determination

SWAMI II will also feature a position determination system being developed by the Georgia Institute of Technology. The system utilizes two CCD cameras mounted on a pan unit with strobes to illuminate retroreflective fiducials placed on the facility walls. Each fiducial has a pattern which the system uses to calculate both the direction and range to the target. The availability of range data will enable the system to calculate SWAMI II's position and orientation more accurately than the system used on SWAMI I. The Georgia Tech system also compares well with the SWAMI I system with respect to operating range: approximately 200 feet versus 100 feet.

SUMMARY

The SWAMI system will provide a safe, cost-effective and comprehensive method to perform mandated inspections of waste drums and obtain useful data for facility and waste management. Because it does not rely on extensive facility modifications, SWAMI will be able to be deployed in a specific facility with a minimum investment of time and capital. By automatically culling out those drums whose condition is acceptable, facility personnel can allocate more time to investigation and disposition of suspect drums.

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David Wagner
Robert Witherspoon

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