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SWAMI IITechnology Transfer Plan

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Introduction

Thousands of drums of radioactive, hazardous, and mixed waste are currently stored at Department of Energy (DOE) sites throughout the United States. These drums are stored in warehouse 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 Savannah River Technology Center (SRTC) Robotics Group of Westinghouse Savannah River Company (WSRC). This system is the Stored Waste Autonomous Mobile Inspector (SWAMI).

The SWAMI program has been funded by the DOE Office Technology Development (OTD), Robotics Technology Development Program (RTDP). The first version of the Stored Waste Autonomous Mobile Inspector, SWAMI I, was developed by the SRTC as a proof of principle system for autonomous inspection of drums in a warehouse. SWAMI I was based on the Transitions Research Corporation (TRC) HelpMate® mobile robot. TRC modified the Helpmate® to navigate in aisles of drums. SRTC added subsystems to SWAMI I to determine its position in open areas, read bar code labels on the drums up to three levels high, capture images of the drums and perform a radiation survey of the floor in the aisles. The radiation survey was based on SRTC patented technology first implemented on the Semi-Intelligent Mobile Observing Navigator (SIMON). The radiation survey is not essential for the inspection of drums, but is an option that can increase the utility and effectiveness of SWAMI in warehouses with radioactive and/or mixed waste. All the sensors on SWAMI I were fixed on the vehicle.

Based on the success of SWAMI I, a second version, SWAMI II, was developed. SWAMI II was developed specifically for drum warehouses at the Fernald site and also included a system to perform a geometric survey the surface of drums. Because of the requirements for the geometric survey system, most of the sensors were mounted on two sensor pods that move vertically to scan drums up to four levels high and also move laterally to center the each pod in front of each drum. Lawrence Livermore National Laboratory (LLNL) joined SRTC in the SWAMI II development. LLNL developed technology for analysis of the images to find rust spots and streaks and analysis of the geometric data to find dents and blisters. The University of Michigan provided hardware and software to drive SWAMI II backwards in an aisle with collision avoidance. This provides the capability of inspecting drums in dead ended aisles at Fernald, where there is not sufficient room to turn around at the end of the aisle. The University of South Carolina provided on-board software for the original SWAMI project, some of which is still used in SWAMI II. The Georgia Institute of Technology

(Georgia Tech) provided an open area position determination system using fiducials that augments dead reckoning in warehouses. Georgia Tech also provided research and development of initial drum finding and structured light analysis systems. The radiation system deployed on SWAMI II was an advanced version based on the Mobile Automated Characterization System (MACS) developed jointly by SRTC, National Nuclear Corporation and Oak Ridge National Laboratory with funding from the RTDP.

SWAMI II will be evaluated at the Fernald site in the fall of 1995. It will be improved based on that evaluation and then tested in the summer of 1996 with two other drum inspection mobile robots funded by the DOE Morgantown Energy Technology Center (METC). The intent is to transfer the technology developed by SRTC for SWAMI I and SWAMI II to industry, so that industry may supply additional units that may be purchased for DOE drum inspection or other drum inspection in and outside the United States. This plan has been developed to transfer this technology to industry.

Summary

The SIMON and MACS technology for floor radiation survey was patented by SRTC and is available for license to industry. This technology is available as stand alone technology or as an addition to the drum inspection system. All of the major support equipment for the radiation sensors and radiation computer, i.e., mobile robot, on-board Versa Module Eurocard (VME) computer, and the UNIX® [1] operator workstation, are included in a SWAMI system, so the incremental cost for floor radiation survey is relatively low. This radiation system would also prevent the spread of radioactive contamination on the floor by a SWAMI system during inspection.

The RADMAP software is being copyrighted and will also be available for license. RADMAP was originally written for the SIMON and MACS systems, but has now been extended to cover most of the operator interface for SWAMI II. The balance of the operator interface, the drum image and geometric display and analysis software developed by LLNL, has been made compatible with RADMAP. Other software, hardware configurations, hardware specifications, designs, drawings, electrical diagrams and experience are intellectual property of SRTC that may be included with negotiations for licenses for the radiologic surveys and RADMAP.

It is planned to offer only non-exclusive licenses for the SWAMI technology, especially the floor radiation survey technology, to provide multiple commercial sources for the drum inspection and floor survey equipment. It is expected that multiple commercial sources would provide cost competition for SWAMI systems. Also, it is expected that multiple commercial sources would provide various and different strengths that could be evaluated for specific drum inspection requirements at a particular site. Transitions Research Corporation (TRC) has expressed interest in producing additional units and would be a logical choice for licensing. However, other mobile robot vendors, particularly Cybermotion, since they are already working with the South Carolina Universities Research and Education Foundation (SCUREF) on a drum inspection system, could apply some or all of the SRTC technology to drum inspection. In a like manner, Lockheed Martin Astronautics may be interested in some of the technology developed by SRTC. The potential for technology transfer to TRC, Cybermotion, SCUREF and Lockheed Martin will be much better understood after the comparison test in the summer of 1996. There also may be interest in providing SWAMI systems

[1] UNIX is a registered trademark of Bell Laboratories and is not an acronym

by system integration companies (integrators). Integrators with robotic experience, radiation experience, hazardous material experience or DOE experience would bring those strengths to a SWAMI system. All of these opportunities for transfer of the MACS and SWAMI technology to industry will be pursued in the next year, with the potential for additional systems inside and outside DOE to be provided by industry expected to become more clear during and after the comparison test.

The transfer of the image and geometric data analysis software must be negotiated separately with LLNL. Discussions on this matter will begin between SRTC and LLNL in early FY96 to develop a technology transfer strategy for this technology before the comparison test in the summer of 1996.

Discussion

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, twelve feet from the floor) 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 SWAMI Operator Interface 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.

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 DOE sites, SWAMI II will initially be deployed at the Fernald Site for evaluation. As a result, Fernald waste storage specifications were used predominately to configure SWAMI II. Waste storage facilities at Fernald are a combination of previously existing process facilities and dedicated storage facilities. SWAMI II is targeted at new, large, tension-supported warehouses at Fernald where the best cost/benefit ratio is expected. Although other containers are present in relatively small numbers, SWAMI II is 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. Initially, many of the aisles only had three feet of aisle at the far end with restricted headroom due to the shape of the tension-supported structure. This would allow vehicle access from only one end and not enough room to turn around at the end of the aisle, requiring SWAMI II to back out of aisles. A backing system developed by the University of Michigan has been installed on SWAMI II to handle this situation. However, backing out would increase the time required for an inspection cycle, would increase power consumption during the inspection cycle and has not been considered by at least one of the other drum inspection systems. Therefore, for the Fernald evaluation many of the aisles at the far end of the rows have been increased to allow for SWAMI II to turn around at the end. Storage facilities typically do not have temperature control, which is the case at Fernald. Several storage facilities have a drum capacity of approximately 12,000 drums, including the tension-support facility at Fernald which will be used for the evaluation.

Radiation Survey

The radiation floor survey is covered by SRTC patent number 5,324,948, Autonomous Mobile Robot for Radiologic Surveys. Licenses for this technology will be offered as an addition to the SWAMI drum inspection technology. Because of the potential for the radiation survey as a stand alone technology, only non-exclusive licenses will be considered. As mentioned previously, the additional cost and benefit of radiologic floor survey as an addition to the basic drum inspection functions of SWAMI make it a logical consideration. Systems using either gas proportional detectors or scintillation detectors have been developed for SRTC by National Nuclear Corporation (NNC). NNC developed a radiation computer that is physically small and has a low power drain, so that it is ideal for a mobile robot application. The NNC computer constantly monitors the sensors and performs an alarm function for alpha or beta/gamma radiation above an operator selectable level. The NNC computer also acquires and stores the data from each detector and communicates these data and any alarm conditions over an RS-232 link to the on-board supervisory computer. This information is sent by the supervisory computer to the operator interface computer in real time over the radio ethernet and displayed on RADMAP. These systems are compatible with the Generic Intelligent System Control (GISC) and GENeric Interface for Supervisor And Subsystems (GENISAS) developed by the RTDP. The NNC system also allows the operator to select parameters, i.e. alarm points, count times, etc., to customize the radiation survey system to a particular site and application.

The radiation sensors on the front bumper of SWAMI II monitor the floor for potential alpha and beta-gamma radioactive contamination as SWAMI II performs its inspection. Five scintillation-type radiation detectors are installed on the front bumper of 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 pre-inspection purge times and gas management equipment are also eliminated. The computer and detector system on SWAMI II is the same as that used on MACS.

RADMAP

The operator interface with the exception of analysis is covered under RADMAP. RADMAP has been greatly extended to include the entire operator interface for SWAMI II including the SWAMI Operator Interface (SOI). The SOI provides remote vehicle controls, a pre-inspection interface, a during-inspection interface, a post-inspection interface, a configuration interface and a link to the analysis operator interface. RADMAP provides a facility map on the operator screen showing the vehicle's current position and status indicated with an icon, all the drums rows, and the major building features, i.e., walls, doors and ramps. The drum row locations for the facility map are automatically produced with information from the modified Fernald Sitewide Waste Information Forecasting and Tracking System (SWIFTS). SWIFTS was modified by SRTC and Fernald engineers specifically for the SWAMI II application. This experience can be used to provide similar modifications for interfacing with other site databases, if required. The SOI interfaces 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. The operator can select standard inspections, an area of rows to be inspected, or specific rows to be inspected by drawing a box over the area or clicking specific rows on the map. The operator also selects a day and time for the inspection to begin. The SOI automatically develops a path for the robot to follow. This path includes a 180° rotation at the end of aisles, if there is sufficient room, or backing out and re-entering backwards to inspect the other side of the aisle, if there Is not sufficient room to rotate at the end of the aisle. If desired, the operator can view the path that SWAMI II will follow in completing the specific inspection. During an inspection the map shows the current location of SWAMI II in the warehouse and can also show a movie which shows the path followed up to that time by SWAMI II during that inspection. The color of the robot icon indicates the current status of SWAMI II. The operator can also choose to view a map or movie of the radiation data collected up to that time. After an inspection, the SOI can call up the analysis results, drum by drum and print out reports of the inspection. The printed reports will include any discrepancies between the expected and discovered inventory. After confirmation by the operator, this information can update the SWIFTS database. Also, the SOI can display a color-coded map of the results of the drum inspection. The color of each drum represents the suspected condition of the drum based on computer analysis. Drum images, geometric inspection data and other SWAMI II file data can also be accessed via the SOI. Radiation data can also be viewed and plotted immediately after the inspection 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. Stationary antennae in the ceiling of the facility provide optimum coverage for SWAMI II. One system has a lower communication (baud) rate, but has the longest range. The other system has a much higher baud rate, which is much better for the large amounts of data required for image and geometric data transfer, but has a shorter range. The best combination of these ethernet systems will be determined for the tension-support warehouse application at Fernald during the evaluation.

Vehicle Supervisory Computer

The vehicle supervisory computer consists of three microcomputers on a half-height VME backplane and other peripherals, including a Local Area Network (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 initial vehicle supervisory computer software was developed by the University of South Carolina. Extensive modifications and additions have been added by SRTC. 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 RTDP. 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.

Base Vehicle

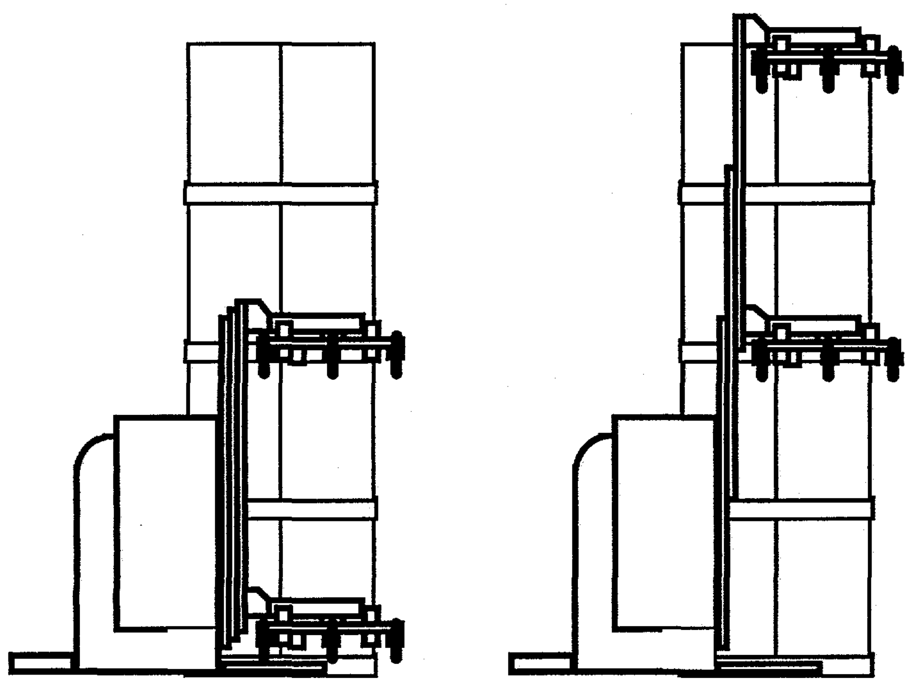
The base vehicle is a modified TRC HelpMate®. Several modifications, such as pallet-sensing ultrasound transducers and vehicle software enhancements, were added by TRC. Other modifications were made by SRTC, including the addition and integration of subsystems. The vehicle is equipped with several systems 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 LIDAR (light distance and ranging) system that uses an eye-safe rotating laser 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 at four different locations on SWAMI II. These not only stop the vehicle immediately, but also stop all motion on the mast added by SRTC. The vehicle's 0.71 m (28 in.) overall width allows it to successfully navigate within the 0.91 m (36 in.) wide aisles at Fernald.

Position Determination

SWAMI II also features a position determination system developed by the Georgia Institute of Technology. This system will augment the dead reckoning and reflective tape positioning systems included with the HelpMate® in the large warehouses at Fernald where frequent facility features, i.e., walls and corners are not available. 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.

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 uses ultrasound sensors to locate each drum during the inspection. One pair of ultrasounds mounted on the vehicle and pointed towards the drum at approximately 45° indicate when the drum is close to the center. During this time a third ultrasound sensor, perpendicular to the robot, indicates when the drum is closest to the robot which identifies the center of the drum. This location is stored and SWAMI II will stop when the nominal center of the sensor pods is at location.



pods in lowest position at start of inspection of column

pods in highest position at end of inspection of column

Figure 1. SWAMI II mast and sensor pods

Mast and Sensor Pods

The mast and sensor pods for SWAMI II were designed by SRTC. On SWAMI I all of the cameras, strobes and bar code readers were stationary on the robot. The structured light system for finding dents and blisters on SWAMI II dictated that the structured light system pass vertically over the surface of the drum. The structured light system also had to extend from the back of robot to allow the lower levels of drums to be inspected. All the sensors including the bar code scanners, color cameras, strobe lights, black and white cameras and lasers were placed on two sensor pods. The lower pod inspects the bottom two levels of drums, the top pod inspects the top two levels of drums. The pods are lifted simultaneously by the mast.

The mast uses a two stage system to provide approximately 102 inches of lift to cover the area from the top of the bottom pallet to the top of a column of 85 gallon drums. Four heavy-duty springs are used to offset the weight of the mast and pods and provide a neutral point at about midway of the vertical travel to minimize the power and energy required to raise and lower the pods. The mast motor has an encoder to accurately determine the position of the mast. It is a DC, servo-controlled, motor to allow accurate control of acceleration, deceleration and speed. The mast is hinged at the top of the HelpMate® so that it can be manually tilted forward to pass through doorways into a warehouse, if required.

The sensor pods extend from the back of the robot during inspection. The pods automatically retract close to the mast to minimize the room needed for rotation at the end of an aisle and also to provide a better center of gravity when traversing a ramp.

SWAMI II will stop to nominally position the center of the bottom pod at the center of the bottom drum. However, each drum in a column may have a slightly different location. Also, the bottom and third level drums are inspected simultaneously. Therefore, each pod has an X and Y motion that allows the pod to precisely center on the drum it is inspecting. This centering is determined by the structured light system and is explained later.

Bar Code Scanners

A bar code scanner is attached to each of the two sensor pods. The bar code scanners are pointed at the left side of the drum where the label is located at Fernald. They read the unique bar code number on each drum. Scanners with a lateral scanning motion are used, since the vertical motion is provided by the sensor pod raising during the inspection. 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. The scanners are continuously looking for bar codes as the pods raise during the inspection. The drum number has a unique initial character, so other bar codes on the label that may be read are disregarded. The scanners collectively communicate with the vehicle supervisory computer through a single RS-485 multidrop port.

Image Capture/Compression/Storage

The SWAMI II image capture/compression/storage system uses two fixed-mount CCD color video cameras and two light strobes on each sensor pod. The cameras are positioned on the pod to capture the left side and center, and the right side and center of each drum as the sensor pod raises vertically. Two sets of pictures of each drum are taken (bottom and center, and top and center) as the pod raises to produce four images, which together show the entire front of each drum. The strobes provide consistent lighting levels for image capture while minimizing power consumption. A VME computer and frame grabber board perform the actual image collection compression and storage functions. At a command from the vehicle supervisory computer that indicates the sensor pods are in the proper position, 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 hard disk. The compressed file is then sent over one of the radio ethernets to the operator station when the ethernet is able to send it.

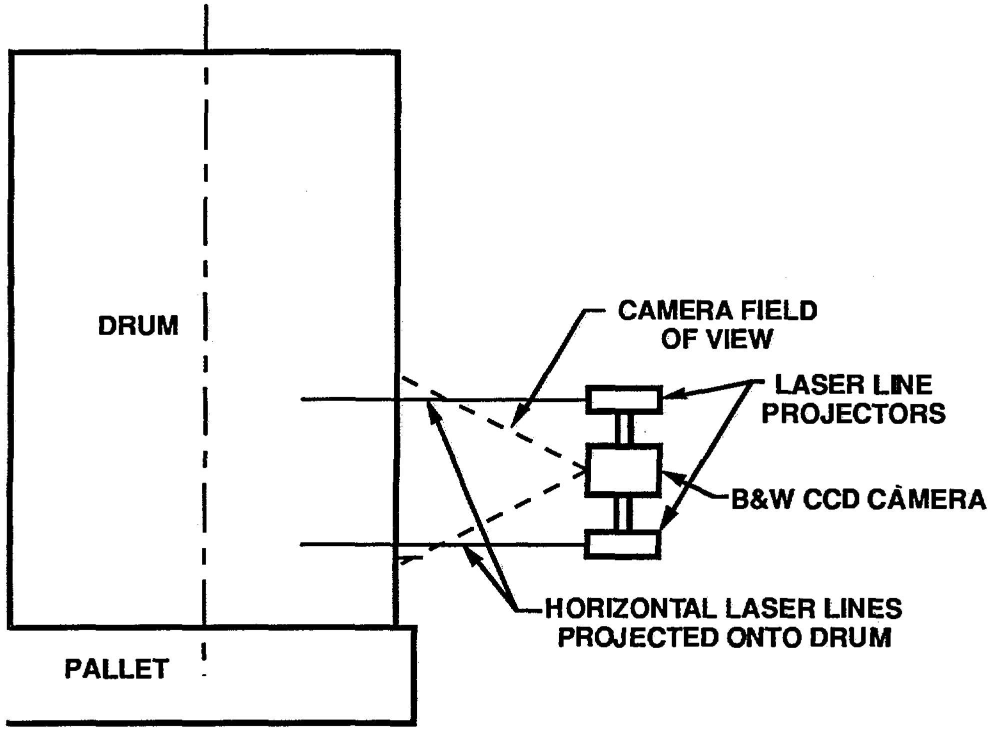


Figure 2. SWAMI II Geometric Inspection

Geometric Inspection

A significant addition to SWAMI II is the 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 on each pod 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 during the inspection.

As the inspection array moves vertically and transitions to subsequent drum levels in the column, any offset from center is manifested by a tilting of the axis of the parabola formed by the lasers as seen by the cameras. Any difference in the distance to the drum surface is manifested by a change in the distance between the laser lines as seen by the cameras. This information is used to move each pod X and Y axis to center on the drum being inspected and provide the correct standoff distance.

In order to provide the required geometry and return intensity three sets of laser line generators and cameras are used on each pod. Each camera has a laser above and below it to operate both at the bottom and the top of the drum where the pallet blocks one of the laser lines (see Figure 2). The three laser line generators above the cameras and the three below are aligned to form continuous lines above and below the cameras. The intensity of the return of laser light from the drum varies with the distance and angle from the camera as well as differences in reflective qualities of the drum. Drum reflective differences are produced by shiny or dull areas of the paint and there are dramatic differences in paint vs. rust and paint vs. white labels. To accommodate these differences the lasers are continuously pulsed at different intensities and an acceptable intensity for each portion of the line is acquired by the software. An interlaced array of the CCD cameras sequentially capture the laser line image as the inspection array moves vertically, parallel to the drum axis. The processed data from the geometric inspection is transmitted to the operator computer during the inspection mission for subsequent computer analysis.

Autonomous Backing

Since many of Fernald's aisles allow vehicle access from only one end, the base vehicle was modified to allow autonomous backing with sensors to prevent collisions. Although the HelpMate® is capable of backing a short distance to recover from a collision, its path planning software does not accommodate following a path while backing and there are no sensors for collision avoidance when traveling backwards. The University of Michigan (U of M) developed an independent ultrasound subsystem which uses 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. This sensor system has been incorporated into the rear bumper on SWAMI II. A relay switches motor control from the TRC system to the U of M system during backing and then switches back to the TRC system when backing is completed. If the aisle does not allow rotation at the end, SWAMI II enters the aisle traveling forwards and inspects the drums to the right of the vehicle. At the end of the aisle, control is transferred to the U of M system that backs SWAMI II out of the aisle, turns the vehicle around and then enters the aisle backwards until the end of the aisle is reached. At this point control is transferred back to the TRC system and SWAMI II inspects the opposite side of the aisle as it travels forwards out of the aisle.

Rust Spot/Streak Analysis

The four color images of each drum and the attached data are transmitted to the operator computer. 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. The areas of concern are highlighted when they are shown to the operator. Drum images and associated data will be archived in a mass storage medium accessible to the operator and other site organizations. Lawrence Livermore National Laboratory (LLNL) has developed the rust analysis subsystem for SWAMI II and the transfer of this technology must be negotiated with LLNL.

Geometric Data Analysis

The geometric data obtained by the structured light system are also transmitted to the operator computer. A Data Cube® computer retrieves the data from the operator computer and performs analysis. This analysis will identify potentially unacceptable dents or blisters on each drum. The structured light data are transformed to a shaded view of the drum, where the shade for each pixel is relative to is distance from the nominal drum surface. The reinforcing ribs on the drum show up very clearly as darker horizontal bands. Blisters are also indicated by a darker shade and dents are indicated by a lighter shade. These areas determined by analysis to be areas of potential dents and blisters are outlined when shown to the operator. LLNL has developed the dent and blister analysis subsystem for SWAMI II and the transfer of this technology must be negotiated with LLNL.