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Drum Inspection Robots: Application Development

by

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ABSTRACT

Throughout the Department of Energy (DOE), drums containing mixed and low level stored waste are inspected, as mandated by the Resource Conservation and Recovery Act (RCRA) and other regulations. The inspections are intended to prevent leaks by finding corrosion long before the drums are breached. The DOE office of Science and Technology (OST) has sponsored efforts towards the development of robotic drum inspectors. This emerging application for mobile and remote sensing has broad applicability for DOE and commercial waste storage areas. Three full scale robot prototypes have been under development, and another project has prototyped a novel technique to analyze robotically collected drum images. In general, the robots consist of a mobile, self-navigating base vehicle, outfitted with sensor packages so that rust and other corrosion cues can be automatically identified. They promise the potential to lower radiation dose and operator effort required, while improving diligence, consistency, and documentation.

The Stored Waste Autonomous Mobile Inspector, or SWAMI, has been supported by the Robotics Technology Development Program (RTDP) and built by the Savannah River Technology Center (SRTC), with assistance from Lawrence Livermore National Laboratory (LLNL). Other systems have been administered by the Morgantown Energy Technology Center (METC) as Program Research and Development Announcements (PRDA's) with OST support. These systems include the Autonomous Robotic Inspection Experimental System, or ARIES, built under contract to SCUREF (South Carolina Universities Research and Education Foundation) by a team from University of South Carolina, Clemson University, and Cybermotion, Inc. Additionally, the Intelligent Mobile Sensing System, or IMSS, was built at Lockheed Martin Space Systems in Denver. Finally, a stand-alone image analysis method entitled Automated Baseline Change Detection (ABCD) system is being developed under a NETC PRDA with Lockheed Martin Missiles and Space in Palo Alto, CA..

The Fernald Environmental Management Project (FEMP) has been an early testing site and has worked extensively with the development teams in an effort to more closely link potential customers to the researchers. This work has included development of site specific inspection procedures and standards, design of a test plan to evaluate the robot's performance, modification of facilities, and the operation and test of the prototypes. To date, only SWAMI has been tested at Fernald, though the IMSS and ARIES are scheduled for testing in 1996. The systems will ultimately be evaluated in a "bake-off", supported by the Mixed Waste Focus Area (MWFA) and organized by Fernald. The comparative test, to be held in about a year, will identify what systems may be ready for commercialization and which parts of others might best be incorporated into a final commercial product. Early indications are that the application is more challenging than first anticipated, due to variations in lighting, environment, facility and drum layout. These circumstances strengthen the need for identification and integration of the best demonstrated available technologies, accomplished through mutual development and competition of alternate technical approaches.

INTRODUCTION

This paper describes the development of a new application for robotics, waste drum and facility inspection, and the effort to evaluate its utility in the field. The work has been conducted at the Department of Energy (DOE) Fernald Environmental Management Project (FEMP), by the Technology Programs (TP) department of FERMCO, Fernald's prime operating contractor. TP has been a technical facilitator, integrating the needs of end-users and efforts of robot developers. To describe this process, the baseline manual practice and generic technology are first outlined, followed by details of the systems that have been built and the on-going program to test them. Experience to date and plans for completing the program are then presented.

Inspection robots perform drum and facility inspections by visually assessing drum condition and other aspects of the facility and inventory. They identify containers by their bar codes, capture and store their images, and evaluate them for signs of damage through machine vision techniques. Corrosion cues identified can include rust spots, streaks, and blisters. Dents, bulges and tilted drums can also be recognized if special purpose sensor suites are included. Other facility inspections may also be performed, including checking the floor for elevated radiation levels or puddles, measuring ambient gamma radiation, or monitoring environmental factors such as temperature, humidity, and lighting. Inventory checking is another possible application, if a materials database is maintained. By automating the initial inspection of the containers, human inspectors only have to physically verify the small subset of containers reported as 'suspect', or possibly damaged, by the robot. The robot must be conservative in its judgements so that damaged containers are never passed as acceptable, even if this means that some containers that are actually satisfactory are added to its suspect container report. Since the primary purpose of the inspections is leak prevention, and not leak identification, suspect drums are expected to be identified before they result in material releases.

Drum inspection robots have the potential to reduce worker exposure to radiological or chemical hazards present in the waste. Inspection quality will also improve through the use of these devices. Consistent performance and diligence result from the robots unhurried, methodical inspections. For containers stacked four pallets high in a facility, drums at the top and bottom of the stack receive the same treatment as those at eye level. The devices eliminate the need for inspectors to stoop down to scrutinize lower level drums, or climb ladders to properly inspect topmost containers. Demands on human inspectors could then be reduced even as inventory increases. While people will always be required in RCRA inspections, robotics can lower the amount of labor required for the activity. The machines provide timestamped, unalterable documentation of inspection activities and drum condition by archiving images and other findings. This improvement in documentation will be a major attraction to RCRA regulators.

TECHNOLOGY SPONSORS AND DEVELOPERS

Assessment of the potential benefits of the application and the maturity of component technologies led the DOE Office of Science and Technology (OST) to support several efforts to develop drum inspection robots. Each system has similar functions, though they offer different technical approaches. The result is that teams from national laboratories, universities and the commercial sector have been able to participate in an exhaustive search for viable solutions. One such robot is the Stored Waste Autonomous Mobile Inspector, or SWAMI, built by Savannah River Technology Center (SRTC), and funded by the DOE Robotics Technology Development Program (RTDP). Image analysis and inspection reporting were developed by Lawrence Livermore National Laboratory (LLNL). Fernald developed SWAMI's archiving and database access routines.

The Morgantown Energy Technology Center (METC) issued Program Research and Development Announcements (PRDA's) for two other full systems. The Intelligent Mobile Sensing System (IMSS) was built at Denver, Colorado, by Lockheed Martin Aerospace. A prototype demonstration was held in April 1995. The Autonomous Robotic Inspection Experimental System (ARIES) robot has been built by University of South Carolina (USC), Clemson University, and Cybermotion under a contract with SCUREF (South Carolina Universities Research and Education Foundation). It was demonstrated in November 1995. METC has also more recently issued a PRDA with Lockheed Martin Missiles and Space for the Automated Baseline Change Detection (ABCD) system, a novel approach to image analysis that compares subsequent inspection results to identify corrosion cues. The DOE Mixed Waste Focus Area (MWFA) recently launched a follow-on initiative to test systems and integrate the best elements into a final, commercial ready system. This represents a renewed and more comprehensive approach towards application development in this field.

APPLICATION DEVELOPMENT PROGRAM

It has been found that though drum deployment in facilities varies significantly across the DOE complex, the need to inspect drums is very common and a growing challenge. At Fernald, the facilities are not highly contaminated, waste inventory has been plentiful and ambient radiation levels are low. At some other sites, the waste emits significant gamma radiation and thus renders the inspection task more hazardous. This has made the Fernald facilities an appropriate initial test area. The goal of the application development and testing program has been to discover the optimum level automation and functionality, in accordance with user desires, current technical capabilities, and common sense.

The full impact of a new technology is difficult for anybody to predict, including waste facility operators. End-users must learn technology limitations, and developers should appreciate the full range of environmental variability in the field. For the drums inspection robotics program, this started with a dialog between the two groups. Specifications matching technology supply to demand could then be generated. Contacts were made with regulators, a set of tests was prepared, performance criteria for application acceptability were outlined, and facility modifications were determined. As projects progressed it became clear that the amount of variability in the field was greater than had previously been envisioned. Teams then had to redesign to meet performance requirements, leading to modifications of testing program scope and schedule. Priorities for Fernald's waste facilities have since changed and its inventory is expected to be eliminated in a short time. Other sites have expressed a strong interest, leading possibly to different application requirements. Thus, the testing program has required almost as many iterations at the technical approaches to the application, demanding flexibility and adaptability.

Identification of user needs was a first task for all the development teams, and they toured several DOE sites to investigate the need and interest in drum inspection robots. In addition to Fernald, several other sites have expressed interest, including the Idaho National Engineering Laboratory (INEL) and Los Alamos National Laboratory (LANL). At the latter site, previously buried drums of transuranic mixed waste are being excavated and will greatly increase inventory, as no disposal has yet been envisioned. Additionally, Hanford had plans to use automated inspections in a new waste processing facility, and at one point was scheduled to demonstrate the IMSS in their RCRA storage areas. Based on the potential applicability on site and the willingness of FEMP Waste Programs Management (WPM) to give SWAMI a chance to show its potential, a demonstration at Fernald was planned early in the RTDP program. Ultimately a single demonstration site at Fernald was selected. TS-4 is a translucent, 90 by 450 foot Tension Support (TS) building with a 12,000 drum inventory in regularly spaced aisles. Fernald information has also been shared with the ARIES and IMSS teams. The ARIES project team has since expressed an interest in tests at Fernald, and the IMSS team followed suit after plans at Hanford fell through.

Early activities were focussed on producing guidelines for the development of the ultimate SWAMI system while an initial testbed, SWAMI I , was being developed at SRTC. Toward that end, a site use requirements document was written that outlined the technical requirements for use at Fernald. This included a request for four-high stack inspection of multiple drum sizes, an 'aisle abort' feature, and full accountability of all drums in the facility. It was noted that the robots must achieve a level of robustness in operation and inspection reliability so as to give credence to its potential for daily usage. The document also surveyed the drivers and practice of inspection at Fernald.

A Work Plan was written to inform the local DOE field office and RCRA regulators in Ohio about the intended demonstration and proposed acceptability criteria. The goal was input from the regulators on what tests would constitute a sufficiently strong case that robots were at least as good or better than human inspectors in certain aspects of inspection. A set of tests to be used in the actual demonstration was described. Success criteria were tuned to the ultimate customer's needs and represented achievable though technically challenging benchmarks. The response from the Ohio EPA was that they would have no comment on acceptance criteria until the technology was more mature. However, they did suggest that the accuracy of current inspections should also be assessed.

A Test Plan was then developed, detailing procedures to systematically evaluate SWAMI for suitability of use in the field. Many of these tests were focussed on production-quality machines that are ready to be operated by site personnel. The original test plan subsequently was modified to match changes in technical scope and schedule. The revision focussed on checking a list of 'baseline' and 'plus' performance goals. The attributes separated achievable near term goals for core functions from desirable but nonessential 'plus' features. SWAMI was then brought to Fernald and tested. A demonstration showcasing SWAMI was held in December 1995.

In the last year, the IMSS and ARIES have also had major demonstrations, in mockup drum storage areas. The MWFA is now supporting an effort to consolidate the work that has been performed to date in this research area and identify the best individual solutions to the overall application. The centerpiece, dubbed the "bake-off", is the comparative test of each robot, in the same facility and in short succession. This will not necessarily be held at Fernald. In advance of the bake-off, a new outreach effort is being made to develop a user's group to supplement early Fernald application guidance to the developers. The users will also be asked to help develop the a new test plan, in conjunction with input from the development teams. The bake-off will occur in early 1997. Before the bake-off, IMSS and ARIES will be given the opportunity to bring up their sensor suites for data collection and then test their full systems at Fernald, as SWAMI has done, over the next six months. The bake-off site will be selected based upon the highest level of commitment to end-use, from the user's group.

CURRENT INVENTORY AND INSPECTION PRACTICE

Clearly an important element of the new application is the environment in which the machine will operate and the baseline practice that it is supplanting. Those issues are considered in this section. At many DOE sites, mixed waste has accumulated in part because of the difficulty in disposing of it. At Fernald, operations resulted in the accumulation of over 100,000 drums of mixed and low level waste. Legacy waste from previous operations is likely to have been originally stored in drums. Newly generated waste is now often placed in B-25 containers and larger boxes because of their better packing efficiency. All stored waste is subject to inspection requirements. The requirement for inspection of Mixed Waste inventory and facilities is found in the Resource Conservation and Recovery Act (RCRA). RCRA is enforced at the FEMP by the Ohio EPA. Low Level Waste (LLW) also is inspected regularly. A consent decree with the State of Ohio drives the activity at Fernald. The growth of inventory and inspection demands lead to the program to develop drum inspection robots.

The machines must operate in storage facilities that range from outdoor concrete pads, to former processing buildings, or unheated temporary storage structures. 55-gallon drums are most prevalent, though other sizes are also used, including 85 and 110-gallon overpack containers. They are stored on pallets stacked up to four high, though three-high is typical. Aisle widths of 36" are most common and encouraged by the Occupational Safety and Health Administration (OSHA), though requirements vary amongst facilities and can be as low as 26 inches.

The inspections are intended to prevent leaking by early identification of corroding drums [1]. Presently, they are performed visually on a daily basis and on a formal weekly schedule to meet RCRA demands. Drums are always positioned so that the side seam and locking screw for the ring that holds the top down are visible because corrosion has been found to start most frequently along the side or bottom seam. Only the visible portions of the drum are inspected. This has been found to be sufficient and reasonable by facility operators and regulators. Suspect drums are categorized according to corrosion severity, with the levels defined in Standard Operating Procedures (SOP's). The most likely cause of container degradation is rust. Dents in the containers can also potentially breach the container or, more likely, act to raise the internal stress of the container in the dented area, thereby making corrosion more likely. Blisters usually start inside the drum, and very small defects can result in leaks. As a rule, containment ability is not affected by general external corrosion if only paint and/or minor metal flaking is occurring. Certain drums are much more likely to leak because of corrosive material within them, and these should be checked more diligently. Freeze cycles and high humidity also accelerate container degradation.

GENERIC TECHNOLOGY AND APPLICATION

The three robots are very similar in the function their machines perform. However, each has a distinct technical approach. Indeed, there are some differences in functionality, as well. The attributes that they all share in common include the main subcomponents: Base vehicle, Inspection sensor packages, Off-board operator controls, Data analysis and presentation, and wireless Ethernet communications (between the host and the robot). Individual components and techniques needed to produce these systems have all been field proven, but the integration of the subsystems into a single machine has proven to be challenging. In order to emphasize the approach towards fair and equal consideration of each system in the bake-off, common elements in all three robots are described here before their individual implementations are introduced. Some of the technical issues faced in application are also detailed.

Self-navigating mobile robots used as the base vehicle for these systems have been under development for over ten years and are commercially available, though the requirements for specific applications often cannot be readily met by off-the-shelf equipment. Several commercial systems have been field-proven to not harm people, the environment or themselves. The basic function of the vehicle in this application is to position sensor packages near each drum in the facility so that it can be inspected, and to house the sensors and actuators that comprise the mission package. For this application, additional battery power for the sensors, a reduced size to navigate in aisles and access all drums, and tolerance to temperature extremes are required.

The machines autonomously travel throughout the facility using an internal map of the environment that originates from the standard CAD files. Navigation techniques including dead reckoning, active or passive landmarks, and local features are used to constantly improve the robot's estimate of its position on that map. Obstacle identification capabilities give the robot the ability to find and then navigate around objects and are accomplished by a redundant set of tactile sensors (bumpers) and non-contact laser or ultrasound ranging systems. Most of the vehicles include autocharging systems so that the robot returns to the base station to recharge when necessary. On-board computers are provided as part of the base robot and the level at which external computers interface with them vary amongst manufacturers. In some cases modifying or externally controlling the machine can be hampered by the manufacturer's restriction of source code access.

Variations in drum position, aisle location, lighting, and temperature are amongst some of the environment-driven challenges for this application. Solutions are available but can complicate system design. In real facilities, aisles are frequently created, rearranged and relocated. They are not necessarily all the same length, or width. Whole drum rows are dismantled to access drums at the far end, resulting in changes in drum and pallet location. Multiple size drums are often stored in a single row, and the arrangement of the drums on a pallet varies from size differences and random placement error. Temperature extremes must be tolerated, since most storage areas are unheated. Some water and ice is also possible. Untended operation is desirable so that the robot can operate when there is less activity in the warehouse. For some machines, night operation is preferred because it reduces the variation and intensity of background light.

Inspection packages on the robots consist of color cameras, strobe light illumination and barcode readers at a minimum. Dents and other topographic features can be inspected by using structured lighting or other methods. With structured lighting, a light emitter such as a laser and a camera that captures the reflected light. The surface can be then be reconstructed using geometric models of the light source, receiver, and ideal drum surface, when the distance from the drum to the robot is known. Multiple sensor packages are used on all of the drum inspection robots to increase throughput since data collection is time consuming. Multiple drum images may be taken to capture corrosion features on the edges of the visible drum surface. The number of images needed is also dependent on the drum size, which can vary in a facility.

Drum center sensors are included in order to position the robot in front of a drum stack. Additional actuators are often used to give the proper standoff for data capture, reposition the cameras for multiple images per drum, and cover more than one level per sensor pod. Supplemental on-board computers are used to control the added equipment and provide an interface to the base vehicle and host workstation. Drums are not necessarily stacked evenly on each pallet, and some systems include fine positioning capability to adjust for offsets either across or along the length of the aisle. Designs must consider the need to inspect all the drums at the far end of dead-ending or dog-legged aisles.

A great deal of data is gathered during robotic inspections. Currently, the robots typically process three or four-high stacks of drums in 60-90 seconds. Multiple images for each drum must be uploaded to the host workstation and commands from the base computer must be received. Wireless Ethernet has been the solution selected by all development teams. The transceivers do not require special frequencies and they support the most common protocols. However, transmission within the stacks of metal drums may be somewhat unreliable. It can usually be improved by moving into direct line of sight with the base antenna. The amount of data transmitted depends on whether images are compressed, if analysis occurs on board, and whether images of non-suspect drums are also retained.

Lighting has a strong effect on the success of image analysis used in the drum inspection application. Images can get overexposed in bright light, sodium lights artificially increase the amount of red in the image, and strobes can create blind spots. Lasers used for dent detection, drum center finding or other purposes are susceptible to wash-out and specular reflections on glossy black drums. Unfortunately, glossy black is a very popular drum color at Fernald. Higher powered lasers can be used but they require special safety precautions that could impede other facility operations. Streaks should not be confused with the handwriting or stencils often found on drums. Red paint on labels or color coding on drum ribs should not be identified as rust. Straps securing top level drums should not be confused with dents.

Special purpose hardware is needed for image analysis. Because of the large amount of data and the sophisticated machine vision techniques used, processing the drum images can be time consuming. Inspection goals were developed for the SWAMI project and represent a reasonable match between technical capabilities and application requirements. Through additional interviews with expert inspectors and input from the new MWFA drum inspection robotics user's group, these values will be revised prior to the bake-off. The current standards are for rust spots greater than 1/4 inch diameter, vertical discoloration streaks larger than 1/4 inch wide and 6 inches long, and dents larger than 1 inch depth, 1.5 inches wide and 2 inches long. A specification for blisters was not identified at that time. However, blisters as small as 1/8 inch in height and diameter have been found to result in leaks. They are also challenging to identify since they may have both discoloration and/or relief cues that must be successfully detected. For all defect features, false positives are somewhat undesirable but false negatives are much less acceptable.

Base stations for the machines consist of a charging area and one or more host workstations. The robot is operated through graphic-based controls that provide for facility set-up, task inception, monitoring and control, results presentation and archiving of inspection records. To check inventory location records, as well as for mission planning and reports uploading, interfaces to site-wide material databases are often provided. At Fernald, an ORACLE database called the Site Waste Information Forecasting and Tracking System (SWIFTS) is used. Several other sites store their waste inventory records in a similar format. Printers, additional mass storage, and high quality color monitors are also supplied. Some of the development teams have envisioned the development of features to reduce the occurrence of false positives. This would allow insignificant artifact or corrosion features to be ignored on subsequent inspections. For rust spots, if the size increases over a threshold between inspections, the feature would again be highlighted.

SYSTEMS UNDER DEVELOPMENT

Place Figure 1 here.

SWAMI

A first SWAMI prototype was demonstrated in a mockup area at Savannah River Site in November 1993 [2]. Figure 1 shows SWAMI II as it was demonstrated in December 1995 at Fernald's TS-4. It is a modified HelpMate robot from Transitions Research Corporation. It has automated battery charger docking and sophisticated obstacle avoidance. It also has many enhancements including local aisle following, a system from the University of Michigan for backing out of dead-end aisles [3], a floor radiation survey system, image capture and processing, and wireless Ethernet. An off-board computer is used as the primary interface to the robot, and a separate VME card cage houses electronics dedicated to image processing. The rad survey system uses scintillation counters instead of gas proportional detectors found in previous SRTC robots. It was tested offline but not as part of the integrated system. The on-board supervisory controller consists of three VME based microcomputers that utilize the GENISAS control software from the RTDP to dispatch tasks between a supervisory control system and various subsystems.

Two sensor pods are positioned by a vertical mast on the robot high enough to cover four-high stacks of 85 gallon drums. The pods are offset by the height of two drums so that the first and third drums are inspected before the second and fourth. Each has cameras and strobes for image capture, a barcode reader, and lasers with black and white cameras for dent detection. Two image cameras cover the required field of view while three sets of two lasers and a camera are used for dent detection. Drum centers in a stack are individually found by a special purpose laser system which then adjusts the position of the sensor pod to achieve optimal height, reach, and lateral offset to the inspected surface by individual linear motions. The lasers are all rated Class 2, which is essentially eyesafe. The pods are attached behind the robot, inspecting only one side of the aisle per pass. They fold so that the robot can spin at aisle dead-ends and then inspect the other side on the return path. If end-of aisle clearance is less that 8 feet, the robot backs out of the aisle and then re-enters backwards so that the other row can be inspected. The data is compressed on-board and transmitted to the base station.

SWAMI off-board equipment includes base station and vision processing computers, printers, and a charging station. The main operation interface for daily system users is called the SWAMI Operator Interface (SOI). Drums to be inspected are selected from a map of the warehouse updated with the latest information from the site's SWIFTS database. Simply by selecting one or more row halves, a mission profile is automatically generated and downloaded to the robot. It also highlights suspect drums that have been found and identifies drums that are out of place as compared to the database.

Images are uploaded and then analyzed on the vision processing computer as they are collected and then uploaded from SWAMI over one of two wireless Ethernet channels. This process starts in the field and continues after the robot has returned to recharge, because of the long time required per picture. The method of rust identification includes color recognition and thresholding, noise reduction and region growing. Streaks are also found based upon their orientation and shape. Structured light data is also uploaded and then analyzed for dents and blisters. The inspection findings are presented through a separate window that prioritizes the drums according to corrosion severity. By selecting a drum with the mouse, a representation of the drum is shown to the operator, with the suspicious areas boxed by the program. Utilities are provided to print out results for physical verification in the field. The images are ultimately stored in a data archive indexed to the SWIFTS database.

Place Figure 2 here.

ARIES

The ARIES robot, shown in figure 2, was first demonstrated as an integrated system November 1995 in a cold test area mocked-up to match Fernald specifications. Hot testing at Fernald early in the summer of 1996 is planned after additional enhancements are completed. Drums of 55-, 85-, and 110-gallon capacity can be inspected in aisle stacks up to four pallets high. ARIES is the first robot to demonstrate inspection of multiple drum sizes, and the only one to inspect 110 gallon drums [4]. It has an autodocking station and is capable of backing and turning around in a 36 inch aisle. Off-board control workstations provide mission planning and monitoring, while wireless Ethernet provides links to on-board computers used for real time mission control and analysis. A power management system, supplemental dexterity package, and a radiation hardening study have also been included.

The machine base is the Cybermotion K3A, redesigned by the vendor to accommodate 36-inch aisles. It navigates using dead reckoning (measuring motion distance and heading changes) and position updates to passive landmarks. The landmarks appear as tennis ball can-sized cylinders covered with retroreflective tape. The reduced size vehicle still has the synchro-drive system that permits six wheels on three horizontal leg units to each be individually steered and/or driven. This improves accuracy of motion recording by maintaining constant wheel contact with the floor. A Camera Positioning System (CPS) is installed on the robot top and moves four instrumentation packages, one for each level. Its stowed height is 10 feet and at maximum extension it is 16 feet tall. The top three levels are positioned using an extending mast in which one linear motion controls the height of the mast and another controls the separation between pods. The lowest level pod is dropped behind the robot using a mechanical linkage. Each image acquisition subsystem consists of a camera with a strobe lamp above and below it. Both strobes are fired in sequence so that reflections can be subtracted from the image. A laser structured light source projecting five dots against drums is used to identify the drum size, drum center location, and tilting. All the lasers used are eyesafe.

Color processing, using specialized algorithms, incorporates supplemental multi-strobe lighting and differential strobe based structured lighting. The design goal was to detect rust larger than 1/2 by 1/2 inch. With wide angle lenses, this leads to a requirement for two images per 55 gallon drum. The images are stored in a Hue-Saturation-Intensity color representation from which a range of values can be attributable to rust. Dent and streak detection are not currently supported though a solution to blister identification is included. This is done by modeling the blister as a conglomeration of small bubbles protruding from the surface, and then performing a frequency analysis of the image intensity. The images are matched and reconnected for clarity in presenting results to the operator. This is achieved by blanking out all regions judged to not be on the surface of the drum, using the projected laser spots in the drum image to guide the cropping process [5]. A single drum is currently processed in six seconds, and the time required to inspect a single four high column and move on to the next is 1 minute. ARIES present throughput is about 2,500 drums per 24 hours.

Robot operation is controlled from a Unix workstation in a portable software environment that has been designed to be scalable to smaller systems for commercialization. However, path and facility simulations that have been developed work best on Silicon Graphics systems. A series of menus guide users or site managers through the facility setup, mission profile, dispatch and monitoring, all activated from the main program. The facility map is derived from an AutoCAD file. A path assembler is used to generate the mission script with location attributes and procedures along a series of linear path segments.

Place Figure 3 here.

IMSS

The IMSS was demonstrated at the Lockheed Martin Denver facility in April 1995. Figure 3 shows the machine as it appeared during the demonstration. Hot testing at Fernald in the spring of 1996 is also planned. Unlike the other two robot development teams, Lockheed Martin built a custom designed robotic base [6]. The welded frame, steel skinned vehicle is quite narrow and can thus enter aisles as small as 30 inches wide. It has special Mecanum wheels that allow it to move or rotate in any direction including sideways. Obstacle sensors consist of ultrasound range sensors and miniature limit switches set behind the sheet metal so that they trip upon contact. They are hard-wired directly into the power distribution system. Aisles are expected to remain fairly constant in location and size, for the current system. The waste facility is described as a main corridor and a series of evenly lined pallet stacks that define the aisles between rows. The robot uses its side ultrasound sensors to align itself with aisle ends and to count aisle entrances. 4-5 hours battery life is the maximum obtainable over the full temperature range specified, using a sophisticated set of sealed Nickel-Cadmium batteries that eliminate the explosion hazard from hydrogen off-gas during recharge. At room temperatures, charge capacity is even greater.

Three fixed sensor arrays are mounted on a vertical mast to inspect up to three stacks of drums concurrently. Extensions to four high stacks are also possible. Each sensor suite consists of two ultrasound sensors used to determine drum centers, a barcode reader, two color cameras and diffused halogen strobe for rust inspection, and a class 3A laser and B/W camera for dent and tilt detection. Two vertical parallel axes of motion move the sensor suites left or right so that the optimal standoff distance and angle is maintained. The mast can swing to the front or rear of the vehicle to inspect drums at the end of an aisle. Four camera shots are required on 55 gallon drums in order to meet detectability goals. Tilt axes on the sensor suites allowed full coverage of the drum from its center.

Images are stored in uncompressed format, but only when defects are found. Multiple sensor arrays are used to improve inspection time. Streaks and blisters were not addressed in the first prototype. Dents on the flat cylindrical surface of the drum, as well as tilting and bulging, were detected using the structured lighting system. Some difficulty was reported with glossy black drums in fluorescent lighting, due to the reflectivity of the surface.

The operator interface presupposes that there might be multiple IMSS robots operating simultaneously. Aisles to be inspected are chosen by double clicking on the spreadsheet entry for that row. Rows are assumed to be all the same length presently. Post-mission, a newly compiled defects database is presented with each feature as a separate spreadsheet entry. The workstation communicates with the robot through a wireless Ethernet. They included the concept of a "baseline" mission, in which a defect database is generated. This database can then be consulted so as to reduce false positives by noting already present defects that are not severe. Now the development team will be integrating the ABCD image analysis system with the IMSS which uses a similar type of baseline inspection method.

Automated Baseline Change Detection

The Automated Baseline Change Detection (ABCD) project seeks to develop enhanced analysis capability for autonomous inspection, that could be useful on any of the robotic vehicles described above. The effort got under way in 1994 and will result in a prototype system ready for demonstration in Fiscal Year 1996. The system compares a current inspection image with an archived baseline image. Any change is identified. If further interpretive analysis verifies that the change is benign, then no action is required. If the change is not benign or is not recognized, then human operators are notified. The key to this process is the use of a commercially available system to identify a target label affixed to all drums, compute sensor distance from the drum, and then rapidly and precisely reposition the sensor. Image transformations are used to match the pose of the newly acquired image to that of the archived baseline.

OPERATIONAL TESTING AND QUALIFICATION

The most important evaluation to be made, and the one that best summarizes robot's effectiveness as an inspector, is the side-by-side comparison of the robot's inspection reports with those generated using existing methods. Thus, during field trials, the waste storage facilities are to be inspected by both the robotic and human inspectors. Accountability for all drums in the warehouse, whether checked by robots or people, is required to guarantee that every drum has been inspected. Throughput and reliability are also very important. All these tests require the machine to be evaluated over as long a time as possible so as to be able to compare machine results against manually generated weekly RCRA reports.

Typically, end-users want to minimize facility changes and developers want to permit facility changes that reduce variability. For SWAMI tests, a moderate set of facility modifications was agreed upon, including the extension of aisle ends and the enlargement of barcode labels. The first test plan, released July 1995, described the full evaluation of SWAMI, its supporting equipment, and the documentation, from the perspective of a DOE site end-user. Its intent was to evaluate a machine nearing production-ready status, outlining ten test methods to evaluate the system from a subcomponent and system level. It called for a Pre-Start Audit addressing basic safety concerns to be completed before other tests are run. A series of offline, or one-time tests were then described, including Safety and Diagnostics, Operator Interfaces, Vehicle Locomotion and Power, Navigation, Barcode Reading and Inventory Checking. During Operator Interface tests, the usefulness and clarity of the controls were to be evaluated as the procedures were simultaneously documented.

It became apparent that intermediate data collection exercises would be necessary before production-quality testing. Other development teams also requested access to the facilities for development purposes. Image data from the warehouses up to that point consisted of video footage and photographs of the drums. Two new types of tests were identified: data collection using individual teams's hand-carried sensor suites, and developmental testing of the robot in the facility, allowing for technical iterations and improvements in the field. The tests acknowledge the value of actual data to the developers. For instance, the design and optics of the camera system, as well as the positioning accuracy of the sensor mast, have a great effect on inspection performance. For the SWAMI project, sensors were brought to Fernald to get better system training data, and this proved very useful in developing algorithms at the laboratory.

In the final SWAMI test plan, radiation detection system tests were removed, others consolidated, and procedures were outlined in greater detail. The final test plan describes two methods to study robot performance over a substantial period of time. The Duration test method compares robotically and manually collected RCRA reports and other key performance attributes, such as the incidence of false positives and false negatives, throughput, and labor requirements with automation. An identification exercise was also included, to compare human and robotic attentiveness. Colored dots were to be randomly placed on visible drum surfaces and then both inspection methods would be compared for completeness of coverage. This test requires additional routines in the robot's image analysis modules, to separately tabulate the count of dots. The other robot feature requested to support testing is a reporting function to record and timestamp selected internal machine variables such as position, heading, or recent actions.

The Inspection Data Capture and Analysis test method focusses on determining inspection accuracy for each corrosion feature type (rust, streaks, dents, blisters), detectability as a function of feature size and location, and sensitivity to aisle placement or drum color. This is accomplished through the addition of a test aisle in the facility. The test aisle consists of a number of empty drums; some of which, called 'ringers', have intentionally placed defects whose description and location have been documented. These ringers are stored, swapped and moved amongst the population of test aisle drums. Four 'Feature Standards' were also included, one for each corrosion feature type. Graduated sizes of dents, rust, etcetera were created on each, from below to above pre-agreed detection limits. The blister standard was made by initiating corrosion from the inside, using a strong acid. Four 'Color Standards' were also created, with random corrosion features placed on red, orange, white, and flat black drums. They were to be used to investigate inspection accuracy as a function of drum color.

SWAMI was received at Fernald in September 1995 and was released in late December, following its demonstration. A technical team from SRTC and LLNL completed system integration and operated the robot during the tests. Access requirements for workers were met with 24 hours of classroom safety training. Baseline functions met during the tests included navigation to straight aisles and through the facility, drum center finding, rotation at aisle ends, image acquisition, barcode reading, and night operation. Data upload rates were determined to be 1,000 drum records in 13.6 hours, and other user interface control and reporting goals were achieved. SWAMI can accommodate drum stacking error with its two linear motions per sensor pod.

Image analysis and geometric (dent) inspection could not be demonstrated as part of an integrated SWAMI system but good results were achieved using images collected during previous data collection exercises. Streak detection, imaging of dents, and rust detection were shown. Blister detection was considered a 'plus' item and has not been completed. Because the inspection software could not be integrated with the robot in time, the two key duration tests could not be conducted. However, SWAMI is expected to participate in the bake-off, at which time it will have an opportunity to be evaluated.

The IMSS and ARIES have both been demonstrated in mockup facilities within the last year and will complete their next developmental phase by the end of 1996.They have not yet been tested at Fernald, and they will have that opportunity this coming year. The step following that is the MWFA bake-off, a side-by-side comparison of the drum inspection robots. A new test plan, set of facility modifications, and success criteria will be developed for the bake-off with fresh input from the end-users, principle investigators, and project managers. The goal is to consolidate the best components from all development efforts into a single robust and practical container inspection robot. A new User's Group is being formed and will be a key contributor to the project. The group will provide guidance as to what functionality should be targeted for demonstration by technologists and a new and revised set of requirements for use at a typical DOE site. They will also be asked to contribute to the development of both the test plan and the criteria used to judge success. The bake-off site will be selected from this group based upon the level of interest and the availability and suitability of facilities for the demonstration. Several sites have already expressed an interest in hosting the bake-off and working these machines into their long-term waste facility operations plans.

CONCLUSIONS

So far, each robot has presented unique capabilities and some shortcomings. Though developmental testing is not yet complete and projects are not at the exact same developmental phase, some comparison is possible based on early demonstrations. The IMSS currently inspects 3-high stacks and features dent detection. It is also the narrowest vehicle, and thus can be used at a greater range of facilities. Inspection results are expected to improve with the addition of the ABCD system, which will be tested on the IMSS during the bake-off. ARIES has done an excellent job in vision system development and is the only system currently inspecting 110-gallon drums and identifying blisters, in stacks up to 4-high. They have not yet addressed streaks and dents, however. SWAMI is very tolerant of real-world aisle, pallet and drum position variations and has multiple redundant systems for obstacle detection. It is also reporting the best results for inspection of glossy black drums and identification of dents on drum rims. SWAMI can only inspect 55 gallon drums currently, however, and presently its laser based inspection and drum centering do not work in bright light conditions.

The need for improvements in inspection accuracy, completeness and efficiency is still strong as is evidenced by interest from various sites. However, the application has proven to be more challenging than originally anticipated. The fact that individual subcomponents have been proven in the field does not imply that a machine full of them will work reliably and robustly in the first design iteration. Because of the diversity of the teams that have independently pursued this problem, solutions to most of the challenges in the application have been demonstrated by at least one team. However, none of them have yet progressed to pilot-scale level performance. With the bake-off site undetermined at this time, an appropriate final testing location will now be sought so that the system is first optimized for an end-use site. Flexibility and accommodation have been required to foster this new application, and will remain important. The path towards integration of system components and technical maturity will not be easy, but the value and potential for drum inspection robotics remains strong.

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