OF

**Intelligent Mobile Sensor System for
Drum Inspection and Monitoring
Phase 1**

Topical Report

June 1993

Work Performed Under Contract No.: DE-AC21-92MC29112

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

For

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Martin Marietta Astronautics Group
Littleton, Colorado

MASTER

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DOE/MC/29112-3641

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Phase I**

DOE

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1000 Independence Avenue
Washington, DC 20585**

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**U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880**

By

**Martin Marietta Astronautics Group
P. O. Box 179
Littleton, Colorado 80201**

June 1993

Abstract

The objective of this research and development project was to develop an operational system for monitoring and inspection activities for waste storage facility operations at several DOE sites. Specifically, the product of this effort is a robotic device with enhanced intelligence and maneuverability capable of conducting routine inspection of stored waste drums. The device is capable of operating in narrow aisles and interpolating the free aisle space between rows of stacked drums. The system has an integrated sensor suite for leak detection, and is interfaced with a site database both for inspection planning and for data correlation, updating, and report generation. The system is capable of departing on an assigned mission, collecting required data, recording which positions of its mission had to be aborted or modified due to environmental constraints, and reporting back when the mission is complete.

Successful identification of more than 90% of all drum defects has been demonstrated in a high fidelity waste storage facility mockup. Identified anomalies included rust spots, rust streaks, areas of corrosion, dents, and tilted drums. All drums were positively identified and correlated with the site database.

This development effort is separated into three phases of which phase one is now complete. The first phase has demonstrated an integrated system (maturity level IVa) for monitoring and inspection activities for waste storage facility operations. This demonstration system was quickly fielded and evaluated by leveraging technologies developed from our previous NASA and DARPA contracts and internal research. The second phase will demonstrate a prototype system appropriate for operational use in an actual storage facility. The prototype provides an integrated design that considers operational requirements, hardware costs, maintenance, safety, and robustness. The final phase will demonstrate commercial viability using the prototype vehicle in a pilot waste operations and inspection project.

Storage Drum with Characteristic Rust Streaks

Processed Image Showing Rust Steaks (Black)
Above and Below Large Rust Spot

Phase I IMSS vehicle in Waste Storage Facility mockup

Close-up of Sensor Scan Platform

Acknowledgments

This project is grateful for the sponsorship of the Department of Energy and Morgantown Energy Technology Center and for the coordination and direction supplied by Gary Nelkin of those groups. We also appreciate the peer review and contacts supplied by Clyde Ward and Dave Wagner of Westinghouse Savannah River Company. We also appreciate the time spent by the Waste Operations Groups at Oak Ridge National Laboratory, Hanford Engineering Laboratory, and Idaho National Engineering Laboratory to provide the application context into which this system fits.

Engineering credit is due to the team involved in this work at Martin Marietta and CH2M Hill. Technical integration, human interface, operator console, data base development and trajectory generation were developed by Dr. John Spofford. Mark Roberts contributed to vehicle electronics, realtime software, communications, obstacle avoidance, and scan platform control. Three dimensional imaging work was performed by Dr. Bill Hoff; all other visual modules for rust detection, streak detection, corrosion detection, label location, etc. were developed by Dan Layne. The executive software and the scheduling software were developed by Dr. Amy Geoffroy. Bob Glade contributed to vehicle electronics, vehicle control, and obstacle avoidance. Tim Charles built all electronic and structural additions and modifications to the system. Judith Stewart provided advice on monitoring and inspection procedures and requirements.

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1. EXECUTIVE SUMMARY

This project developed a prototype mobile robot to autonomously monitor and inspect stored waste containers. The problem to be solved was weekly inspection of large numbers of stored 55 gallon drums containing unspecified hazardous, radioactive, and mixed wastes. These drums are stored in large warehouse-like facilities in rows or groups with aisle widths down to 0.75 meters and stacked up to three levels high. EPA requires all barrels to be monitored weekly. Reports must positively identify each barrel inspected and must generate a separate report for those barrels not meeting the inspection limits. Barrels should be inspected for dents, bulges, rust, oxidation, radiation leaks, and gas leaks. A cost analysis gave costs of \$56/hr. robotically and \$195/hr. manned for equivalent inspection tasks. Other significant benefits accrue for safety, accuracy, and consistency.

The base contract (phase one), discussed in this report, developed an integrated system using available hardware to demonstrate and parameterize the mobile robot and the sensing system. Phase one had a period of performance of 8 months. The overall project is composed of three phases where phase two develops a commercial prototype and phase three provides an extended duration demonstration to prove commercial viability and robustness. Figure 1 shows the timeline in months for the project, with the milestones defined relative to the start of each phase (ATP). Table I defines the milestones for the three phases of the project.

Figure 1 - Three Phase Milestone Schedule for Intelligent Mobile Sensor System Deployment

Table I - Milestone Definition Log

Phase	Milestone	Definition
I	Vehicle Complete	Testbed vehicle enhanced for proximity maneuvering. Mission sensors characterized and mounted to vehicle and manipulator.
	Software Complete	Mission executive software complete. CAD map and data procedures created after site visit. Operator interface to database and executive complete.
	Evaluation Complete	Testbed system demonstrated in representative site and performance evaluated.
II	Critical Design Review	Detailed engineering design for field deployable system is complete. Review of design has occurred with no significant discrepancies. Ready to manufacture.
	Prototype Complete	All hardware and software elements integrated and tested. Ready to ship for site demonstration.
	Site Demonstration	Prototype system has demonstrated inspection and survey operations at operational site.
III	System Complete	Integrated system is complete and ready for delivery to site. Any modifications indicated during previous demonstration have been incorporated.
	Project Complete	System has been successfully deployed for six months at operational site.

There were five main elements of the phase one engineering effort:

- define the sensing problem and environment, the format of the solution, and additional application sites;
- integrate the vehicle;
- develop and integrate the executive software;
- develop and integrate the mission sensors; and
- perform testing to determine performance and cost parameters.

A significant effort was performed to ensure the solution reached was useful and efficient for actual monitoring activities. This includes analysis of the reporting procedures as well as discussions concerning additional implementations at other sites. Figure 3 shows a typical waste storage facility.

The vehicle was integrated from subsystems some of which previously existed including the motion platform, the sensor mast, and the operators console. Other components that were added included the ultrasonic obstacle avoidance system, the sensor suite, omni-directional wheels, and the navigation software. A complete safety system was installed with rigorous handshaking command-response sequences and with several automatic safing procedures. A photograph of the vehicle is shown in Figure 2.

Figure 2 - Intelligent Mobile Sensing System (IMSS) Vehicle

Development of mission sensors focused primarily on video and laser elements. This was a new development effort and the sensors and software have been installed on the vehicle. Figure 4 shows a closeup of the sensor mast and scan platform. The laser system is Class II which is eyesafe. Close-ups of processed images are presented in Section 5.4.5.2.

Figure 3 - Engineering CAD

THIS DRAWING IS IN ACCORDANCE WITH ASME 10.1
 CAPACITY RATE OVERSPREAD 10.1
 SEE PARTIAL PLAN SK-2-58811

AN
 DRUMS PLACED INTO AND
 RETRIEVED FROM STORAGE
 WITH MANUALLY OPERATED
 FORKLIFT.

APPROVAL
 CONCEPTUAL

Drawing of a Typical Waste Storage Facility

U.S. DEPARTMENT OF ENERGY TONAWANDA FIELD OFFICE WASTE MANAGEMENT DIVISION	
MECHANICAL LONG TERM DRUM STORAGE PLAN	
DATE: 10/10/80	SK-2-58811 10

Figure 4 - Closeup of IMSS Vehicle Sensor Mast

Executive and scheduling software for mission control and report generation was coded and installed. This software is initiated from the operator console (Figure 5), which also provides access to control of the vehicle at other command levels as well as providing access to the site and report data bases.

Figure 5 - IMSS Operator Interface

Phase one culminated in a series of parametric tests to measure sensor and vehicle performance. These data will be used subsequently in phase two to build a robust, cost effective prototype. The defined success criteria in the phase one contract was as follows:

- locate and report damaged barrels, simulated leaks, and inaccessible areas:
 - > 90% detection rate;
 - < 20% false positive alarm rate.
- autonomously navigate the test site avoiding obstacles and drums, and return to the home position, as a function of the operator input / task description.

The measured detection rate for the phase one engineering model exceeded 91% positive detections in all categories of visual anomalies, with fewer than 14% false positives in all categories. The performance standards for phase one were for detection of visual anomalies. Tested visual anomalies included rust, rust streaks, corrosion, dents, and tipped drums. Anomaly order and background conditions (lighting, viewing angle, and anomaly size) were varied. Measured detection rate is a statistical compilation of the representative set of anomalies and conditions using results from multiple autonomous test runs in our WSF mockup. An example of rust detection and identification is shown below.

The Intelligent Mobile Sensing System provides a general capability for carrying sensors into hazardous areas and autonomously inspecting or mapping the features of concern. Derivative applications arise from installing different sensors on the mobility base. In this sense the mobile platform supplies power, a data system, and autonomous positioning of the sensor heads in the desired location. Other reasonable applications include real time autonomous concrete characterization, sensing in very radioactive locations such as canyons or other process areas, and dig-face sensing.

Figure showing input image from color video camera (left) and processed image (right). Detected rust spots (1 large patch, 2 small spots) are automatically highlighted for analysis and reporting.

2. INTRODUCTION

This phase one final report documents the initial effort of this project to develop an integrated engineering prototype and to perform parametric testing to acquire data for a subsequent design. This report contains sections describing:

- Purpose (§3.0),
- Background (§4.0),
- Methodology (§5.0),
- Results and Discussion (§6.0), and
- Conclusions (§7.0).

The section on "Purpose" describes the DOE application need and discusses system requirements and derived requirements.

The section on "Background" provides additional information both on inspection procedures currently approved by DOE and EPA as well as information on benefits and costs.

The section on Methodology is subdivided into four major sections:

- System Design and Integration (§5.1),
- Test Facility (§5.2),
- Engineering Development (§5.3), and
- Parametric Measurements (§5.4).

The section on "System Design and Integration" discusses the system architecture and subsystem block diagram, and the design of the individual subsystems including new equipment and software as well as previously available equipment. The section on the "Test Facility" describes the facility mockup that was built to provide a test environment for performance measurement. The section on "Engineering Development" includes discussions on the software development environment, the video development environment, and the hardware prototyping facilities and techniques. Finally, we discuss subsystem and system parameters of concerns, and tests that were performed to acquire the data required for the subsequent phase two design.

The final major section is on "Results and Conclusions." This section provides the results of testing and parametric measurements, and discusses the affect these might have on the phase two redesign.

3. PURPOSE

The purpose of this effort is to create a system to automate the monitoring and inspection process for stored hazardous, radioactive, and mixed wastes. The Department of Energy has hundreds of thousands of storage drums stored in multiple facilities located on several sites in the United States. The EPA requires positive weekly inspection of each storage drum in a storage facility. This inspection process is time consuming and presents inherent health hazards.

The proposed system will automate the inspection process, lowering costs and providing safer, more accurate and more consistent inspections.

Representative EPA and DOE approved inspection procedures from Hanford and Rocky Flats are presented and discussed in §4.1. From these requirements, and from discussions with waste operations personnel at four DOE sites (Oak Ridge National Laboratory, Hanford Engineering Laboratory, Idaho National Engineering Laboratory, and Rocky Flats Plant), the functional requirements shown in Table II were developed. All requirements were met in Phase I. Other derived requirements are shown in Table III.

Table IIa - Functional Requirements for System

Automatically Generate Reports
Minimum Operator Inputs
Navigate Autonomously
Avoid Unknown Obstacles
Inspection time less than 60 seconds per drum

Table IIb - Functional Requirements for Mission Sensors and Anomaly Detection

SPECIFIC REQUIREMENT	PHASE I CAPABILITY
Dents: Detect round or pointed dents (> 1")	Detected dent depths as small as 0.5"
Tilts: Identify tilted drums	Detected down to 2 degrees of tilt
Displacement: Identify missing or displaced drums	Identified missing drums; relocated drums within 3"
Bar Codes: Scan labels; identify missing labels	Read bar code labels; identified drums missing labels
Rust: Detect, quantify and track surface rust	Identified spots smaller than 0.1"
Streaks: Identify rust streaks	Can differentiate rust streaks from water streaks
Corrosion: Detect, quantify and track corroded paint	Identified bubbled paint down to 0.1"

Table III - Derived Requirements

KEY DRIVER	DERIVED REQUIREMENT
Operate in Waste Storage Area	<ul style="list-style-type: none"> - 36" width for mobility base - sensors operate in dim light - sensor placement device for reaching stacked barrels 20' high or in combination with directional probe or sensor. - proximity sensor for obstacle detection and avoidance
Operate in Highly Contaminated and Hazardous Areas	<ul style="list-style-type: none"> - shielded against radiation effects - shielded against corrosive chemicals
Safe operation in environment	<ul style="list-style-type: none"> - fail operational to ensure return to base and no collisions or runaways - non-sparking to avoid volatile combustion - bumper sensor for immediate stop on contact
Perform Mission Without Human Intervention	<ul style="list-style-type: none"> - intelligent vehicle executive - map based planner - realtime sensor based control - sensor based replanning
Detect Anomalous Characteristics	<ul style="list-style-type: none"> - provide background and directional measurement capabilities for volatiles and radiation - detect rust patches, dents, scratches
Log Locations and Characteristics of Anomalous Measurements	<ul style="list-style-type: none"> - provide data archiving on board vehicle - transmit to console at mission end - provide navigational measurements to establish location of events - archive visual information for anomalous events - provide bar code and label reading system
Characterize Nature of Contaminants	<ul style="list-style-type: none"> - modular sensor suite for multiple instruments - be able to install instruments for detailed investigation of leaks (eg. spectrometers) - sample collection system
Provide Realtime Control and Feedback to Operators if Necessary	<ul style="list-style-type: none"> - allow direct operator control of all autonomous operations as necessary - communication link - workstation with teleoperated control - provide display of vehicle location, site map, measurement data and vehicle status
Generate Inspection and Monitoring Reports	<ul style="list-style-type: none"> - be able to operate on database to select and correlate desired information - automatically print out reports after inspection
Report Mission Status	<ul style="list-style-type: none"> - executive planner must record status of its tasks - auto print map and path
Accomodate Future Unknown Tasks	<ul style="list-style-type: none"> - modular interfaces for additional equipment (data, electrical, mechanical) - instrumentation bus NIMS bus - extra space on top of vehicle

4. BACKGROUND

4.1. Inspection Procedures

Representative EPA and DOE approved inspection procedures are shown in Tables IV and V from Hanford and Rocky Flats respectively. From these requirements, and from discussions with waste operations personnel at four DOE sites (Oak Ridge National Laboratory, Hanford Engineering Laboratory, Idaho National Engineering Laboratory, and Rocky Flats Plant), the functional requirements shown previously in Table II were developed. A further discussion of these requirements and procedures occurs below. It is noted that few specifics are provided in the documentation and consistency between sites is not maintained.

Most storage facilities have barrels stored four to a pallet and have pallets stored in single rows. Observed stacking heights varied from two to five drums with an average of three. Aisle widths varied from 25" to 30" to 36". Aisle lengths varied from 20 feet to hundreds of feet. In general, space was left between the last pallet in a row and the adjacent wall.

Positive inspection of each barrel is required. Operator response to flagged barrels is required within 24 hours. All barrels must be inspected at least every six days.

In performing a visual inspection for mixed waste storage, a human operator should evaluate the condition of the drums in order to determine the integrity of liquid containment. Professional judgement should be used to identify those negative conditions that may result in the escape of any liquids, or in the case of radioactive waste, any drum condition which may result in a release of air-borne contamination, such as alpha particles. With these qualifiers in mind, the following extracted requirements are used:

- sharp or pointed dents - no depth greater than one inch, width or length not critical.
- rounded dents - ignore unless the stability of the drum is in question.
- surficial rust (paint corrosion) - track diameter size; if rust is increasing, identify.
- streaks of rust - identify source; if source is from outside and rust is surficial, ignore (water on top of drum, leaking roofs, standing water); if source is from side of drum or from under lid, identify.
- non-surficial rust (metal corrosion) - identify by diameter.
- tilted (bulging) drums - if drums are banded, identify if base of drum is touching bottom storage surface (pallet, plywood, or floor); if drums are not banded, identify if tilted (any angle greater than two degrees); identify if ribs of drum cannot be distinguished.
- stacking levels - for specific storage area, identify if stacking level is exceeded.
- condition of pallets or plywood separating drum levels - identify if broken.
- location of bar codes - upper third of 55-gallon drums or top half of 35-gallon drums, the top of the bar code not more than two inches below drum seal, visible from the aisle.
- location of hazardous waste labels - if the site requires hazardous labels, the label should be located in the center third of 55-gallon drums, or top half of 35-gallon drums.

The above information is flexible because of differences of the regulating agencies and DOE facilities.

From these rules and guidelines the following barrel inspection requirements were incorporated into the IMSS system:

- Locate and read barcodes to positively identify drums. Report if barcode is missing.
- Visual anomalies to detect and classify:
 - dents over one inch deep,
 - tilted barrels,
 - missing or defective barcodes,
 - rust and corrosion
- Types of corrosion to identify and parameters to record:
 - Rust (surface area)
 - Rust Streaks (length)
 - Corrosion (blistering, chipped, peeling, or missing paint) (surface area)

- Coloring of barrels includes:
 - white,
 - grey,
 - black,
 - yellow, and
 - silver.
- Visual anomalies NOT to be processed include:
 - accumulations of dust or dirt on ridges, rims, or seams,
 - condensation streaks of dust or dirt, and
 - symbols or other labels that are not barcodes.

Other considerations are present that must be considered when inserting new technology into the current monitoring and inspection process. Some of these are discussed below.

- The same report forms should be created by the IMSS as are currently created by the inspectors. In general these should be completed once per week per area.
- An operator must be positively called if a defective barrel is identified to ensure the condition is corrected within 24 hours.
- A map of the area should be included on which the defective barrel is identified to aid the operator in his response.
- The integrity of the process must be maintained to ensure that computer files indicating required operator activity are not deleted by an operator without being reported to the supervisor.
- It should be noted that the development of the IMSS opens additional possibilities for record keeping including tracking drum status over time. Also all records are already computerized and can be stored on any high density storage medium of choice for integration with other data systems.

*Table IV - Waste Storage Facility Inspection Procedures Extract (Hanford)
for RCRA Hazardous Waste Container Storage Units*

General Inspection: Basis 40 CFR 270.14(b)(5), 264.15(b), and 264.33
Periodic inspections (daily, weekly, monthly) by operations personnel
Planned maintenance inspections of buildings, equipment, and operating systems
Industrial monitoring system printout (ie. continuous air monitoring or remote area monitoring for mixed waste units)
Operation checks and calibrations of CAMs and RAMs
Periodic radiological surveys by health physics personnel using portable instruments
Scheduled and random inspections/audits by emergency response, security, safety, and quality assurance organizations
Needed corrective actions noted on commitment tracking system or similar instrument
Inspection of Records
Inspections Specific to Container Storage Units: Basis 40 CFR 264.15(b)(4) and 264.174
Permitted or Interim Status Units the same (excepting secondary containment requirement)
Frequency:
- Weekly, minimum (less than or equal to six days between inspections)
- Daily in high risk areas (loading and unloading)
Inspect container storage area for:
- leaks
- container deterioration / condition
- containers stored closed
- condition of floor coatings, curbing, other means of secondary containment
Must make container condition determination for all (100%) containers (negotiable). Base negotiations on factors such as waste form, presence of free liquids, ALARA concerns, etc.

CONTAINER STORAGE AREA WEEKLY INSPECTION LOG SHEET

BUILDING
ROOM
CONTAINER STORAGE AREA ID NO.
DATE
TIME
SIGNATURE OF INSPECTOR

The following logsheet must be filled out completely and accurately. The only acceptable responses are "Yes", "No", or "N/A". Inspections must be performed weekly so that no more than six days elapse between inspections.

Form WTS, Rev. 10/1/84

1. Is hazardous waste only being stored in authorized areas?
2. Last inspection was in 7 or under days?
3. Is spill response equipment adequate, accessible and in good working condition?
4. Area ID sign(s), present, correct and visible?
5. Is area posted "Danger - Unauthorized Personnel Keep Out"?
6. Container(s) located within authorized boundaries?
7. Is base underlying containers free of cracks or gaps?
8. For liquids, is secondary containment present and in good condition?
9. Are containers in good condition?
10. Is the hazardous waste compatible with the container?
11. Is there any other hazardous waste being accumulated?
12. Are the containers closed?
13. Are containers in a locked or fenced area?
14. Area free of spillage, leakage or other accumulated liquid?
15. Is perimeter fence or walling and roof in good condition?
16. Container label(s) correct, legible and visible?
17. Is operation log for WFMST current and available?
18. Is there adequate aisle space, which is clear of obstruction?

H. Freeze Protection Inspection?

- * Inspect the container for holes, dents, bulges, rust, damaged seams or signs of leakage.
- * Signs of incompatibility include: bulging, blistering, turning or temperature increase.

REMEDIAL ACTIONS

ALWAYS NOTIFY SUPERVISOR OF ANY PROBLEMS

* NO ANSWERS REQUIRE EXPLANATION AND/OR CORRECTIVE ACTION IN THE COMMENTS SECTION

COMMENTS and CORRECTIVE ACTIONS:

(If additional space is required the reverse side of this logsheet may be used for comments)

	DATE
	DATE
	DATE
	DATE

FIGURE C. Container Storage/Treatment Inspection Logsheet

4.2. Comparison of Stored Waste Monitoring Techniques

4.2.1. Current Stored Waste Monitoring Techniques

The current methods used to inspect and monitor stored wastes are based on either passive detectors or on humans walking through the storage area with various instruments.

Passive monitoring relies on fixed sensors dispersed within the containment building. Often these are only alpha detectors. When an increase in radiation is measured, operators must enter the storage site and locate the leaking container. Walking inspections usually include alpha detectors, gas detectors, and visual inspections. Visual inspection of the drums is required to detect dented, bulging, or rusting drums. However, visual methods are a function of operator acuity and fatigue level and may vary between operators and even between individual drums. Operators may receive varying radiation doses during their inspections and must be examined for contamination prior to site exit. Required drum inspection frequency and operator lifetime radiation limits raise the effective cost of this monitoring process and introduces health and safety risks.

4.2.2. Advantages of Proposed Solution

4.2.2.1. Public and Occupational Health Risks

A major advantage is the reduced human exposure afforded by this system. Inspectors no longer need to enter the building to monitor the stored waste. The extended exposures during normal inspection add up quickly given the required frequency and total number of stored waste containers. Thus, using this autonomous system will eliminate the occupational health risks associated with this activity. This is even more important in the event of a discovery of a leak, or of collapsing barrels which have inestimable costs in possible long term injuries. In fact, in the event of a leak, an autonomous system, equipped with a manipulator with advanced impedance control and contact stability algorithms, can use a siphon tool and bung puller to remove the material before removing the barrel and risking breaking open full containers during transit.

4.2.2.2. Environmental Risks

Environmental risks can be greatly reduced by a quicker detection of leaks. By ensuring frequent inspection of storage sites, leaks can be detected more quickly and remedial action initiated sooner to reduce the total amount of wastes leaked into the environment. Likewise more consistent checks will ensure adequate inspection of all barrels and avoid "dark corners" and "end of the aisle" syndrome. Finally, by being able to correlate minor changes from inspection to inspection, it may be possible to detect evolving problems before they become major ones.

4.2.2.3. Operations

The advantage of the proposed autonomous sensing system to operations is better, more detailed, consistent records. This includes individual verification of each individual barrel by barcode without an oppressive burden of report generation. Automating the monitoring and report generation process allows development of a continuous database which can improve the accuracy and accountability of the overall ER&WM process.

Another operational advantage is that barrels can be examined quicker (in terms of barrels per week) allowing the sites to more easily comply with the RCRA regulations.

4.2.2.4. Cost

This cost comparison assumes equal productivity between man and machine in terms of the time required to inspect a single barrel. For a discussion of this assumption, see the next section.

Assumptions for cost of manual operations include items for total cost and usable productivity level:

- one full time inspection team (two inspectors) costs \$150k/yr. including costs for wages, overhead (suits, sensors, etc), support (exit exam and decontamination, etc), and training.
- use of time during an eight hour shift includes 4hrs/day inspection, 1hr for preparation and transit, and 3 hours per day for reporting.
- inspectors require 16 hours training per month (on average) or 4 hours per week.

Assumption for robotic operations in terms of cost and productivity include the following:

- cost of mobile sensor system after initial prototype is \$200k/vehicle
- vehicle operates 8 hours on, 4 hours recharge per shift, two shifts per day
- vehicles do not operate on weekends
- required support is 30 minutes per trip task loading and report generation by a human operator; 8 hours per week maintenance (nonproductive time plus labor charge), installation support of \$10k per room (beacons and map generation).

Given these assumptions, calculated costs per year for the two different methods are as follows: manned - \$150k/yr. and automated - \$210k/yr. The calculated productivity for each system in terms of hours of inspection time are: manned 768 hrs/yr (52 weeks - 2 weeks vacation - 2 weeks holidays = 48 weeks per year. weekly productivity is 4 hrs/day * 5 days per week - 4 hrs/week training = 16 hours per week. Total productivity is $48 * 16 = 768$) and automated 3744 hrs per year (52 weeks per year; weekly 16 hours per day times 5 days minus 8 hours maintenance = 72 hours per week. Total productivity is $52 * 72 = 3744$). Given these costs and productivity an overall comparison is shown below:

manned - \$195/hour

automated - \$56/hour

This is a large difference and several parameters should be examined before using these numbers as part of a cost/benefit analysis. First amortization of the R&D costs of the vehicle need to be considered (although the cost is already paid for by DOE/OTD). Of course these must be spread over the number of years of monitoring and inspection anticipated, must include all sites with similar activities (at least four in this application alone), and must include the total number of vehicles at each site. The total number of vehicles at each site is of course dependent on the number of storage containers present or number of buildings, but it should be noted the overhead of supporting five vehicles is the same as supporting one vehicle in terms of operational and maintenance personnel. Likewise, if one chose to operate the vehicles on weekends, one would increase vehicle productivity by 29%.

4.2.2.5. Time

To verify the assumption of at least equal inspection time per barrel, consider the following statements. When a human inspects a barrel he must examine his instruments while swiping or pointing them at the barrel thus requiring two activities; the mobile sensing system monitors instrument data streams in parallel with its pointing activity. In terms of visual inspection, the human must analyze his visual inputs while looking at the barrels and determine on the spot if there is a blemish or fault. The mobile sensing system takes a picture at an appropriate spot and then analyzes the picture during transit to the next barrel. Also, unlike a human, the machine does not change inspection speeds during lapses in concentration or toward the end of a shift.

4.2.2.6. Waste Minimization

Another major advantage of the mobile sensor system accrues from waste minimization. Routine entrance of people into the store rooms is eliminated, eliminating the garments that would have been used and disposed of. The vehicle would be stored in the building and can be hosed off when it has to be removed.

4.2.2.7. Institutional and Regulatory Goals

This technology will increase controllability and accountability for the stored wastes by having an ensured, consistent, and frequent record.

5. METHODOLOGY

This effort is part of a three phase program to commercialize autonomous monitoring and inspection technology. The objective of the first phase is to have demonstrated an integrated system performing the required functions; the objective of the second phase is to package the software and components for an actual hot demonstration in a real storage facility; the objective of the third phase is develop the product to an certified, commercially viable system. The phase one demonstration of an integrated system is used to gather parametric performance data regarding task performance versus vehicle hardware and software parameters. This allows the design in phase two to be optimized regarding cost, performance, and reliability. For instance, the required navigational accuracy can vary as a function of motion characteristics, sensor characteristics, control system characteristics, and presence of navigational beacons. Design trades can be made as to encoder resolution, inclusion of navigation beacons, the need for an inertial measurement system or GPS transceiver, and path planning and correction techniques.

The phase one effort assembled an integrated engineering model including all components required to perform the functional requirements. The system was tested in a small scale storage facility mockup to gather performance data. The following sections describe the effort in terms of:

- system design and integration,
- test facility description,
- engineering development environment, and
- parametric performance measurements.

5.1. System Design and Integration

The system hardware included many existing systems and components in order to lower development costs and reduce the required development time. The engineering model that was assembled performed all functions but not in the form eventually required. For instance the vehicle width did not meet the aisle width requirements. Of course vehicle width does not affect image analysis or autonomous capability. Likewise, the sensor mast was suitable for barrels stacked two high, but not for barrels stacked three high. Again, this does not affect the monitoring and inspection requirements; all vehicle design modifications will occur in phase two.

5.1.1. Architecture

The system functional architecture is shown in Figure 6. This architecture is based on a standard reference model for automated systems developed by the National Institute of Standards and Technology (NIST) and subsequently ported to NASA for their space program. The architecture provides a modular structure that enhances modularity, both for portability and extendibility. This model is similar to DOE's Generic Intelligent System Controller (GISC) architecture in terms of providing standard interfaces and call to subsystem components. This architecture is hierarchical in nature wherein all control of components at a lower level is encompassed by a module at the next level up. The architecture is divided into two logical areas, sensor processing and autonomous control, which are linked to a multilevel operator interface. This structure separates control functions from sensing functions but still allows them to communicate as necessary through a world model. The multilevel interface allows interaction with the hierarchy of control functions at several levels. In normal operation, only the highest level is used (e.g., start inspection procedure). Other levels are available for development or for applications that require direct teleoperation such as surveying an unknown area for entry characterization of an extremely radioactive environment. Note that the multilevel interface also plays a role in safing procedures as well as lower level replanning when the system becomes blocked.

Figure 6 - IMSS Functional Architecture

A subsystem block diagram is shown in Figure 7. This shows the basic motion platform subsystems for vehicle mobility and control in the lower block. These items include the structure, wheels, drive motors, controllers, obstacle avoidance subsystem, and navigation subsystem, as well as support functions such as power, communications, computation, and safety. The components of the scan platform are on the right side of the diagram and are mixed between the upper and lower block. Hardware included are the pan and tilt actuators and controllers. The scan platform is responsible for pointing the sensors in the right direction, and providing communications and power. The upper block contains those subsystems required for the mission sensing software. This includes the particular sensors, sensor software, executive software, and the task application software that resides in the operator's console.

Figure 7 - IMSS Subsystem Block Diagram

5.1.2. Mechanical Subsystems

5.1.2.1. Motion Platform

Three degree of freedom cartesian vehicle motion (x , y , ϕ) is achieved by using four independently driven omni-directional wheels. This arrangement allows forward/backward, sideways, and rotational motion independently or simultaneously. Motion in confined spaces is greatly simplified compared to that achievable using conventional steering. Also, simple cartesian path planning may be used to position the vehicle precisely for measurements.

Mecanum Wheels - The Mecanum omni-directional wheels are composed of eight rollers mounted on axles at a 45 degree angle from the wheel axle. The rollers are mounted around the circumference of the wheel and are free to rotate when in contact with the ground. Only one roller is in contact with the ground at any time and because the rollers longitudinal cross section is convex it is only in contact at a single point. The additional degree of freedom added to the wheel by the roller in contact with the ground enables 2 degree of freedom motion (x and y) of the contact point without requiring wheel slip. Rotational slip normal to the contact surface at the single point of contact is required for motion involving vehicle rotation. To provide 3 degree of freedom vehicle motion two sets of wheels are required. The right front and left rear wheels have contacting rollers mounted at a positive 45 degree angle to the vehicle longitudinal axis where as the left front and right rear wheels have contacting rollers mounted at a negative 45 degree angle. By using independent wheel motion controlled by vehicle inverse kinematics, three degree of freedom (x , y , ϕ) vehicle motion is achieved.

Wheel Drive Train - Each wheel is driven by a dc brush motor through a spur gear transmission with a 100:1 gear reduction. 512 count per rev incremental position encoders are located at the motor to provide wheel position sensing for control.

5.1.2.2. Sensor Platform

The scan platform is a two axis gimbal located at the front of the vehicle. It provides pan and tilt motion for various mission sensors including the stereo cameras, color camera, and bar code reader. The LASER striper and camera lamp are also mounted on the platform.

Motion Control - Motion control is implemented using two channels of a Galil DMC530 motion control board. The board closes position loops with PID controllers and provides $\pm 10V$ differential signals to drive custom built PWM amplifiers which drive the pan and tilt motors. Both scan platform gearmotors are Faulhaber Schonaich 3557K DC motors with 66:1 reductions. See Sections 5.1.3.1 and 5.1.4.2.

Position Sensing - Position sensing is accomplished with one US Digital Softpot S2-1024IB incremental optical encoder per axis. These encoders have a resolution of 1024 counts per revolution and generate index pulses. The outputs are decoded using the standard quadrature state method by the Galil boards, effectively quadrupling the encoder resolution. The tilt axis encoder is connected directly to the tilt platform and therefore has a resolution of 4096 counts per revolution. The pan encoder is geared at 3.3:1 to the pan platform and therefore has a resolution of 13516 counts per revolution.

Position/Velocity Limits - The pan axis is limited in software to a position range of ± 120 degrees from home and a velocity range of 1 to 10 degrees per second. The tilt axis is limited in software to a position range of ± 35 degrees from home and a velocity range of 1 to 10 degrees per second.

Power Up Condition. - The vehicle powers on in a manual abort condition. As soon as the condition is remedied, the pan and tilt axes are automatically homed to a zero position. Independent home signals are generated with infrared emitter/detector pairs mounted to each axis. When the Galil board receives a home axis command, the axis is moved in a direction that depends on the state of the home signal. When a transition on the home signal is detected, the axis is moved slowly to the encoder index pulse and halted.

Safing - Both axes have position limit switches that disable the corresponding amplifier when actuated. The pan hardware position range limit is approximately ± 130 degrees from home. The tilt hardware position range limit is approximately ± 40 degrees from home. The pan and tilt amplifiers are also disabled by a manual abort.

Command Capabilities - The scan platform control task will perform the following functions:

- Power control for the LASER striper and the camera lamp.
- Homing of both axes.
- Absolute or relative position moves at specified velocity.
- Velocity moves.
- Abort of current and queued commands.

5.1.3. Electrical Subsystems

5.1.3.1. Vehicle Electronics

The control electronics package for the Phase I demonstration vehicle consists of a VMEbus card cage and motor amplifiers as shown in Figure 8.

Figure 8 - Control Electronics.

VMEbus Card Cage Electronics

The VMEbus card cage contains commercially available boards, including a Force SYS68K/CPU30 single board computer, two Galil DMC530 Motion Control boards, a XYCOM XVME240 Digital I/O board, and a XYCOM XVME230 Intelligent Counter Module.

The Force SYS68K/CPU30 single board computer is based on a 25 MHz 68030 in conjunction with a 68882 math coprocessor. The CPU30 is fitted with Ready Systems VRTX/Velocity PROMs. VRTX/Velocity is the real-time multitasking operating system used by the vehicle software. The CPU30 also offers an Ethernet connection, serial ports, and 4M of RAM.

Motion control is provided by two three axis Galil DMC530 Motion Control boards. These boards provide adjustable PID controllers for the wheels and the scan platform motors. The position sensing incremental optical encoders are connected directly to the DMC530s.

System digital discretes are controlled and monitored by the XVME240 Digital I/O board. This board has a 64 signal capacity, configurable as 8 bit ports of inputs or outputs. The current configuration splits the ports, providing 32 inputs and 32 outputs. These signals are used for power state control for system components, monitoring of abort conditions, and other system functions.

The XVME230 Intelligent Counter Module interfaces to the ultrasonic ranging system. One 16-bit up counter on the board is used as an event counter to acquire the distance to objects for each of the eight ranging channels. See Section 5.1.3.2.

Motor Drives

The wheel motors are driven by independent custom built PWM amplifiers based on the Advanced Motion Controls AMC-500 hybrid PWM amplifier. The amplifiers accept $\pm 10V$ differential control signals and produce +28V pulse width modulated drive for the motors. The current limit for each amplifier is 8A. This limit is well above the expected normal operating conditions.

The scan platform motors are driven by independent custom built PWM amplifiers based on the Linear Integrated Circuits L292 Switchmode driver. The amplifiers accept $\pm 10V$ differential control signals and produce +28V pulse width modulated drive for the motors. The current limit for each amplifier is 2A. This limit is well above the expected normal operating conditions.

5.1.3.2. Ultrasonic Transducers

The Ultrasonic Ranging System is capable of detecting objects at a minimum range adjustable from 0.7 to 1.3 feet and a maximum range of 32 feet. The stated typical absolute accuracy is 1% of the reading and the detection angle is approximately 10 degrees.

There are eight ultrasonic sensor modules located around the vehicle perimeter as shown in Figure 11. The electronics configuration is shown in Figure 9. Each sensor module consists of a Polaroid 616342 electrostatic transducer and 615077 ranging board. These modules are connected to a common custom built electronics package. The electronics package accepts software controlled digital discretes. Assertion of a control signal to the electronics package initiates transmission by the corresponding transducer. At the same time, a 1 MHz square wave is fed into a 16 bit counter on the VME board. When the transducer detects an echo, the square wave is disabled. The value in the counter is then related to the distance of the object that caused the echo.

Figure 9 - Ultrasonic Ranging System Electronics

5.1.3.3. Communications

All communications above the hardware control level were implemented using the TCP/IP protocols on Ethernet. The network interfaces were implemented with the project-standard TCP/IP library. This library provided standard function calls for establishing a server, opening a connection, reading data, writing data, and testing for the availability of data. This library was implemented on all the Unix computer systems, as well as the real-time VRTX embedded control system.

The IMSS vehicle for phase one used a communications and power tether. Communications channels were a thin Ethernet link to higher-level control system elements, and composite video lines to the sensor processors.

5.1.3.4. Power

Power is supplied to the vehicle from two sources. The primary power source is a set of lead acid batteries that supply up to 40A. The secondary power source is two parallel 28V, 12A linear DC power supplies. The power supplies charge the batteries when the vehicle is off, and trickle charge the batteries during intermittent operations. The off-board supplies are connected to the vehicle +28V bus via a 75 foot tether consisting of three 12 AWG Power/Ground pairs. This allows a maximum IR drop of 1.3 volts. IR drop in the tether is significant since the supplies are configured to sense locally. If remote sensing is used with these supplies, IR drops of about 1V cause instability resulting in power supply damage.

The +28V bus provides power directly to the wheel, pan, and tilt motor PWM amplifiers. It also supplies the necessary input power for DC-DC converters which provide the vehicle system with +5 and ± 12 VDC.

5.1.4. Control

5.1.4.1. Vehicle

Vehicle movement is commanded in cartesian coordinates (x,y,phi) via autonomous point to point position commands or by velocity commands from a teleoperator using three degrees of freedom of a hand held joystick. Position commands are resolved in a fixed world coordinate frame whereas velocity commands may be resolved in either the fixed world frame or the moving vehicle body coordinate frame. Figure 10 shows the vehicle motion control block diagram.

Figure 10 - Vehicle Motion Control Block Diagram

This architecture implements vehicle position control indirectly by the control of vehicle wheel speed. A cartesian velocity trajectory is generated subject to acceleration and velocity constraints. This velocity trajectory will, if followed precisely by the vehicle, deliver it to the desired cartesian position. The required wheel speeds to follow the trajectory are calculated from the cartesian velocities using the inverse jacobian derived from vehicle kinematics. (variables are as defined in the text and shown in Figures 10 and 11)

Inverse Kinematics

Vehicle inverse kinematics determine wheel velocities for desired vehicle motion:

$$\underline{w} = \mathbf{JINV} \underline{v} \quad 1$$

The wheel and Cartesian vehicle velocity vectors:

$$\underline{w} = \begin{bmatrix} w_{LF} \\ w_{RF} \\ w_{RB} \\ w_{LB} \end{bmatrix} \quad \underline{v} = \begin{bmatrix} v_X \\ v_Y \\ v_f \end{bmatrix} \quad 2$$

The inverse Jacobian:

$$\mathbf{JINV} = \frac{1}{r_w} \begin{bmatrix} 1 & -1 & -(l_a+l_b) \\ 1 & 1 & (l_a+l_b) \\ 1 & -1 & (l_a+l_b) \\ 1 & 1 & -(l_a+l_b) \end{bmatrix} \quad 3$$

Wheel Speed Control

This velocity based control approach relies on vehicle wheel speed control. Off the shelf Galil motion controllers are used with incremental motor encoders to close digital PID position loops around each wheel. A wheel speed control mode is available using the Galil controller which internally generates an acceleration limited position reference for each wheel position control loop to reach the commanded speed.

Odometry

Because the vehicle will not exactly follow the velocity trajectory, an estimate of the actual vehicle position is calculated from wheel speed derived from encoder measurements. Estimated vehicle velocity is calculated using the forward vehicle jacobian and integrated to obtain the vehicle position estimate. Position estimate error build up due to wheel slippage and other sources is periodically eliminated by establishing absolute position using the vision system in conjunction with landmark targets whose positions are known.

Forward Kinematics

Vehicle forward kinematics determine vehicle motion given wheel velocities:

$$\underline{v} = \mathbf{JFWD} \underline{w} \quad 4$$

The forward Jacobian:

$$\mathbf{J}_{\text{FWD}} = \frac{r_w}{4} \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & -1 & 1 \\ \frac{-1}{l_a+l_b} & \frac{1}{l_a+l_b} & \frac{1}{l_a+l_b} & \frac{-1}{l_a+l_b} \end{bmatrix} \quad 5$$

Collision Avoidance

A collision avoidance mechanism is provided to prevent contact with unknown or out of position objects. Eight ultrasonic range sensors located around the vehicle perimeter as shown in Figure 11 provide range information indicating the proximity of objects in the vehicle environment. This range information is used to develop a virtual force potential that in effect wards off the vehicle from the object. When scaled properly the force potential resulting from an immanent collision with an object may not be overcome by any motion command that would otherwise result in a collision with that object. A virtual force calculated from ultrasonic range information acts on the vehicle at each sensor location resulting in a net force and torque at the vehicle center (vehicle reference coordinate frame origin). To actually apply the virtual force and torque to the vehicle through the controller requires generation of a velocity command using the force and torque. The relationship between force and velocity defines a mechanical impedance for which the simplest example involving mass is a second order dynamic system. Using for example a mass-damper model to generate velocity commands from virtual forces and torques results in a well behaved relation that allows adjustment of sensitivity and speed of response of the vehicle to obstacles.

Virtual Force Filter

The virtual sensor force vector:

$$\mathbf{f}(\mathbf{r}) = \begin{bmatrix} f(r_{FL}) \\ f(r_{FR}) \\ \dots \\ f(r_{LF}) \end{bmatrix} \quad 6$$

The virtual force at a sensor is determined from the measured range:

$$f(r_i) = \frac{k_i}{2} \left(\frac{1}{r_i - w_i} - \frac{1}{d_i} \right)^2 \quad 7$$

Sensor Kinematics

Transform sensed ranges to virtual forces on vehicle:

$$\mathbf{E} = \mathbf{J}_F \mathbf{f}(\mathbf{r}) \quad 8$$

The Jacobian combining and transforming virtual forces from sensor frames to vehicle frame:

$$\mathbf{J}_F = \begin{bmatrix} -C_{FL} & -C_{FR} & \dots & -C_{LF} \\ -S_{FL} & -S_{FR} & \dots & -S_{LF} \\ y_{FL}C_{FL} - x_{FL}S_{FL} & y_{FR}C_{FR} - x_{FR}S_{FR} & \dots & y_{LF}C_{LF} - x_{LF}S_{LF} \end{bmatrix} \quad 9$$

The parameters for the sensors (eight at present) are as follows:

Sensor i	θ_i	C_i	S_i	x_i	y_i	w_i
FL	0	1	0	+	+	
FR	0	1	0	+	-	
RF	$-\pi/2$	0	-1	+	-	
RB	$-\pi/2$	0	-1	-	-	
BR	π	-1	0	-	-	
BL	π	-1	0	-	+	
LB	$\pi/2$	0	1	-	+	
LF	$\pi/2$	0	1	+	+	

2nd-Order Impedance Filter

The virtual forces, resolved in the vehicle reference frame:

$$\mathbf{E} = \begin{bmatrix} F_X \\ F_Y \\ T_F \end{bmatrix} \quad 10$$

The difference filters that convert virtual forces into commanded velocities:

$$v_{XOFFk} = a_{xy} v_{XOFFk-1} + g_{xy} v_{XOFFk-2} + h_{xy} (F_{Xk} - F_{Xk-1}) \quad 11$$

$$v_{YOFFk} = a_{xy} v_{YOFFk-1} + g_{xy} v_{YOFFk-2} + h_{xy} (F_{Yk} - F_{Yk-1}) \quad 12$$

$$v_{fOFFk} = a_f v_{fOFFk-1} + g_f v_{fOFFk-2} + h_f (T_{Fk} - T_{Fk-1}) \quad 13$$

The parameters a_n , g_n , and h_n are determined off-line for desired dynamic response:

$$a_n = \frac{2 J_n + B_n D t}{J_n + B_n D t + K_n D t^2} \quad 14$$

$$g = \frac{-J_n}{J_n + B_n D t + K_n D t^2} \quad 15$$

$$h = \frac{D t}{J_n + B_n D t + K_n D t^2} \quad 16$$

where J_n , K_n , and B_n are the mass/inertia, damping, and stiffness to be emulated. Separate parameter sets n are used for translations xy and rotation f .

[illegible]

5.1.4.2. Scan Platform

Scan platform motion is controlled via pan and tilt angular position commands with associated acceleration and rate limits. The Galil motion controllers described in §5.1.4.1 are used to close PID position loops on the pan and tilt axis. Incremental encoders are used to sense pan and tilt rotation axis positions. The Galil controllers are used in the position control mode. Absolute position of the pan and tilt axis is determined during initialization using a homing scheme that searches for the index pulse of the incremental encoder. Positive and negative motion limit sensors are used to safely limit the range of pan and tilt motion.

5.1.5 Navigation

The vehicle navigation system is based on a combination of two methods: wheel odometry and landmark sightings. Figure 12 shows a block diagram of our approach. This approach combines the best of both methods: continuous data availability from odometry and absolute position knowledge from landmarks. Odometry position estimation uncertainties that grow with travel distance are reset to zero by occasional sightings of known landmarks. A minimum amount of facility preparation is required, with no paint or tape applied to the floor. These two methods are described in the following sections.

Figure 12 - Block Diagram of Navigation Approach

5.1.5.1 Wheel Odometry

Wheel odometry is the simplest form of navigation, also known as dead reckoning. The IMSS vehicle has omni-directional wheels designed to operate without translational slip. This allows estimation of vehicle position and orientation within the facility based on a time history of the wheel angular velocities. The process involves sampling the wheel positions at a fixed rate, differencing the positions to get the velocities, applying the kinematic velocity transformations between wheels, vehicle body, and facility reference frames, and integrating the resulting facility frame velocities to get the position and orientation. This estimated data is available at the basic servo-loop rate for coordination of vehicle and scan platform motion. Error sources include kinematic modelling errors (e.g. wheel diameter) and wheel slippage on the floor. These are compensated for using landmark sightings as described in the next section.

5.1.5.2 Landmark Sighting

A model-based machine vision technique locates the position and orientation (pose) of a landmark target relative to the vehicle. The target is distinguished by a set of features, concentric circles, in a pattern predetermined pattern defined by a model. The principles of operation for the target recognition and pose estimation used are detailed in [Hoff] and [Gatrell]. Landmark targets are required at fixed, known location in the facility. These targets are flat and can be affixed to any stationary surface, such as walls or columns. A representative target is shown in Figure 13. The image is acquired using the same video camera that acquires the corrosion-detection images. The advantage of this method is that it uses no additional sensors on-board the vehicle. The barcode and text on the target allow for unique identification of a specific target from all

others. The main pattern of features (the concentric circles) is the same for all landmarks, but the barcode uniquely identifies a specific target. The location of all landmarks is stored in the facility database, indexed by the barcode identifier. The pose of the vehicle in the facility is computed from the pose of the target relative to the vehicle and the database location of the target.

Figure 13 - Representative Landmark Target

Sightings of landmarks are commanded by the mission executive process under two circumstances: Regular sightings based on predicted odometry estimation error; and special sightings when a drum position-type defect is detected. Drum position-type defects include a missing drum and a drum not located in the expected position.

5.1.5.3. Path Planning

The present approach uses off line generation of point to point position command scripts.

5.1.5.4. Trajectory Generation

Position commands from the executive are used to build an acceleration and velocity limited velocity trajectory to move the vehicle from its present position as measured by odometry to the commanded new position in a smooth and orderly fashion. Maximum velocity and acceleration time to maximum velocity are programmable. The velocity trajectory is updated at the vehicle servo rate (.1 sec) and used to calculate wheel speed commands using vehicle inverse kinematics.

5.1.5.5. Obstacle avoidance

The obstacle avoidance capability is currently not coupled to path planning. It operates independently to provide velocity inputs to the vehicle control system. Its operation is discussed in 5.1.4.1.

5.1.6. Sensing Subsystems

5.1.6.1. Laser Ranging

The laser ranging sensing subsystem is used to perform inspection of the three-dimensional characteristics of the drums. Specifically, the tasks of initially locating the drums, detecting surface dents, and measuring drum tilt, are essentially three-dimensional tasks — *i.e.*, they require accurate measurement of three dimensional points on the surface of the drums. In addition, a dense set of 3D points is required, so that small dents are not missed. The resulting dense set of 3D points can be put into the form of a range image, in which the integral positions of a two dimensional array represent directions, and the values stored in the array represent the range to points in the scene. Assuming the sampling intervals are consistent in the horizontal and vertical directions, the (i,j) position of an element in the array implicitly determines the 3D direction vector to that point. The term "range image" is used because the array can be displayed on a video monitor and in fact has the same form as an ordinary video image. The only difference is that the values in the range image represent distance instead of light intensity.

Range Imaging Techniques.

There are numerous techniques available to generate range images. Surveys in the literature include Jarvis [1983] and Besl [1989]. Two classes of techniques particularly suitable for the drum inspection task are: laser radar and triangulation. Laser radar uses time of flight to directly measure distance from the sensor to a point on the drum. By scanning the beam, a complete range image can be built up. Although these

systems are fast and accurate, we did not use a laser radar due to its relatively high cost (\$100K+), power and weight requirements.

Triangulation techniques use the known relative position between two sensors, or a sensor and a light source, to infer the distance to a point on the drum through trigonometry. Two types of triangulation techniques are passive stereo vision and structured light. In stereo vision, two cameras simultaneously generate a pair of images of the scene, from which feature points are extracted independently and matched between the images. From the known relative positions of the cameras, the 3D locations corresponding to the matched points can be determined. Stereo vision is very general and is the principal method by which human beings perceive depth. However, for a dense set of feature points to be extracted from the images, the surfaces being imaged should be visually textured (e.g., markings, dirt, corrosion, etc). This property would not necessarily be true of smooth, clean drums. It is possible to illuminate the surface of interest with a random synthetic texture pattern, which ensures that sufficient feature points are available to be matched (Schewe and Forstner [1986]). A more significant disadvantage of stereo vision is the computational difficulty of reliably matching feature points.

Structured light is a triangulation technique in which a light source such as a laser is used to project a known pattern (such as a point, line, or grid) onto the scene. A sensor is rigidly mounted a known distance away from the light source such that it images the projected pattern. Again, triangulation can be used to determine the range to points on the projected pattern. A mechanical scanning system is required to build up a complete range image. Structured light systems have long been used in the machine vision field, primarily for industrial inspection applications (Shirai and Suwa [1971]). Currently, there are numerous commercial systems available; e.g., from Technical Arts Corp, Robot Vision Systems Inc, and Perception. The advantages of structured light systems are low cost and accuracy. Disadvantages include: the time required to scan the scene, and limited depth of field.

Overview of Our Design

We elected to use structured light as the range sensing technique for our task of drum surface inspection. This selection was driven by our need for a low cost, accurate system. The disadvantages of slow scanning time and limited depth of field were not perceived as sufficiently major to eliminate this technique from consideration. We developed our own structured light system consisting of a laser line projector, two CCD cameras, and an image processing workstation. The laser and cameras are mounted on a pan-tilt mechanism to allow scanning of the entire scene (see Figure 14). This design was motivated by the fact that all the equipment, with the exception of the laser line projector, was already available. (The laser line projector, a Lasiris Inc. model SNF-512, was a nominal \$800 additional.) Also, in an operational system, image processors and frame grabbers will likely be present anyway, to perform rust and corrosion inspection.

Figure 14 - Structured light laser imaging system.

The 20 mW solid state laser is Class IIb by itself (medium power, danger). However, we enclosed it in a box so that the intensity of the light stripe as it exits the box is less than 1 mW over a standard 7 mm aperture. This brings the classification down to Class II (low power, caution). The wavelength of the laser is

680 nm. We placed long pass filters on the cameras with a cutoff wavelength of 670 nm, to eliminate most of the background light.

The use of two CCD cameras provides a measure of redundancy, since a single CCD camera can be used for triangulation. However, two cameras also improves reliability, accuracy, and coverage of the system. Reliability is improved since we can require both cameras to agree on the same 3D result in order to output that point. This eliminates occasional false returns due to multiple reflections off specular surfaces. Accuracy is improved because the range results from the two cameras are averaged. Coverage of the system, meaning the amount of the scene from which we get actual range data, is improved because there are fewer "shadowed" areas with two cameras than with one.

Figure 15 shows a range image of a "swath" through three drums standing adjacent to each other. The brightness values of the image represent distance. Here, we have subtracted the actual range values from a constant in order to give a more natural appearance. The blackest values in the image represent "dropout" points; i.e., points from which no distance was measured. Figure 16 shows the equivalent range image drawn as a surface plot. A rib of the middle drum is clearly visible in the surface plot. Also visible is a dent above the rib.

Calibration Procedures.

The purpose of the range imaging system is to generate an accurate range image with respect to the vehicle. In order to do this, we must calibrate the imaging system with respect to the vehicle. There are 4 steps involved in doing this:

- 1) Calibration of each camera with respect to the laser. This allows each camera to determine the 3D positions of points with respect to a coordinate system attached to the laser.
- 2) Calibration of the laser with respect to the pan and tilt axes. This allows 3D points which have been located with respect to the laser system, to be determined with respect to the scan platform.
- 3) Calibration of the zero point and the scale of the pan and tilt axes. This allows 3D points which have been located with respect to the movable scan platform to be determined with respect to a fixed coordinate system coincident with the scan platform. In our system, the zero point is determined manually by aligning the scan head so that its axes appear parallel to the vehicle's axes. The scale is determined by knowledge of the gear ratios and encoder counts per revolution.
- 4) Calibration of the fixed scan platform coordinate system with respect to the vehicle coordinate system. In our system, this is determined by manual measurement.

We have developed automatic procedures for performing calibration steps 1 and 2 above. Step 1 is performed by a procedure in which a ruled surface is moved through a series of positions in front of the laser system. At each position, stripe points are extracted from the image, and the corresponding range (Z value) of each of those points is recorded. The vertical (Y value) locations of the points are also recorded. By definition, the laser stripe lies in the Y-Z plane of the laser coordinate system, so the X values of all imaged points are identically zero. From these series of measurements, a complete lookup table can be interpolated. The resulting lookup table is in the form of two images, one for Z and one for Y. In operation, whenever a stripe point is extracted from an image, the 3D position of the point can be directly read from the lookup table images.

Step 2 of the calibration procedure determines the location and orientation of the pan and tilt axes with respect to the laser. This step makes use of a technique called "inverse perspective," which is the technique by which a single perspective view of a known object is used to recover the location and orientation of that object. Numerous inverse perspective techniques have been developed in the fields of photogrammetry and computer vision (see for example, Fischler and Bolles [1981] and Haralick, *et al* [1989]). The first step is to calibrate the internal parameters of the cameras (i.e., focal length, lens distortion, and horizontal scale factor). We use the technique of Tsai [1987], with optical targets designed for rapid and accurate feature location (Sklair, *et al* [1990], Sklair, *et al* [1991]). Inverse perspective algorithms take as input the camera parameters, a geometric target model, and a set of image feature locations with correspondences to the target model. The output of the algorithms is the six degree of freedom position and orientation (pose) of the object with respect to the camera.

To calibrate our cameras with respect to the laser, we create a virtual target model using the Y-Z lookup tables. From these lookup tables, we can extract a set of (X,Y,Z) points as well as their (x,y) image locations.

Figure 15 - Range Image of Three Drums

Figure 16 - Surface Plot of Range Image

An inverse perspective algorithm determines the pose of the laser with respect to each camera. The next step is to determine the pose of each camera with respect to the other camera. This is done by simultaneously observing with both cameras the same calibration target, computing the pose of the target to each camera, and then the pose of the cameras with respect to each other.

We then determine the location and orientation of the pan and tilt axes with respect to the cameras. This is done by observing a target at one position, determining its pose with respect to the cameras, moving the pan (or tilt), and observing the target again from the new position. From the two computed poses to the same target, we can estimate how the cameras moved from one position to the next. In this manner, the pan and tilt axes are found with respect to the cameras.

Algorithm description: locating drums

During operation, when we go to inspect a drum, we must first determine its location. There are two reasons for this: (1) we don't know precisely where it is, and (2) we need to determine if the drum is tipped (which could indicate bulging of the ends). Our first step is therefore to take a range image in the direction of the expected location of the drum and locate the drum in the image.

There are many algorithms in the literature for processing range images and recognizing objects (for a survey, see Besl and Jain [1985]). Many of these involve extracting surface patches from the range data and matching them to object features. However, our application of finding drums is much simpler because the drums have such a simple geometric model. For the purpose of finding the drums, it is sufficient to treat them as cylinders of a constant known diameter (ribs, dents, and rims show up as small geometric deviations from the model). We have developed a simple algorithm based on the above model, which is described as follows.

The first step is to estimate the surface normal at each point in the range image. This is done by fitting a plane to the local neighborhood at the point. We then take pairs of points at random from the image. For each pair, we compute the direction of the cross product of their surface normals. If the two points lie on the drum, the cross product vector should point along the axis of the drum. If the two points are not both on the drum, the cross product will point in some other (random) direction. The largest cluster of cross product vector directions gives the direction of the drum axis.

The next step is to determine the location of the drum axis. From the previous step, we know which points in the range image are likely to lie on the drum. Since we know the radius of the drum, we know that the drum axis lies inwards along the surface normal at a distance equal to the radius. Therefore, for each point hypothesized to lie on the drum surface, we project a ray inwards along the surface normal to a distance equal to the drum radius. We then project a line along the drum axis downwards until it intersects the floor. By clustering these intersection points, we can find the intersection point of the drum axis with the floor.

This procedure is tolerant of some occlusion of the drum surface, the presence of background objects, and the presence of dents and ribs. The status at the time of this writing is that we have a working standalone prototype that we have tested on synthetic range data. We are working towards testing it on real range data and getting it integrated into the rest of the system.

Algorithm description: locating dents

Once a range image has been taken and the drum located within the image, we must next find dents. Here, dents are defined to be deviations from the nominal drum surface of over 0.5" vertical depth and having a lateral area of 7.8 square inches (50 sq. cm.). Our approach for this algorithm is to take the known location and size of the drum and determine which points in the image lie within the specified depth tolerance of the ideal drum surface. Those points that do not lie within the specified depth tolerance are possible dent points. We will exclude ribs because they will lie at a radius greater than the known drum radius. Points which lie at a radius less than the nominal drum radius will be clustered into regions. Those regions larger than the specified surface area are flagged as dent regions.

5.1.6.2. Vision

Visual anomalies (rust, streaks and corrosion) on storage drums are detected with a color camera and image analysis software. The subsystem configuration is shown in Figure 17. The color video camera head is a JVC TK-870U using a single CCD element. A 16 mm lens is being used, based on comparing various lenses for the drum inspection requirements. Two or three images per drum will be needed for medium resolution inspection (locate pea-sized rust spots). The camera is located at the center of the vehicle scan

Figure 17 - Vision Subsystem Configuration

platform. Adjacent to the camera are two compact 20W video (halogen) lamps which are turned on only during image acquisition. The lamps help illuminate rust and streaks under variable lighting conditions. For inspection, the camera is nominally positioned at about 90cm from the drum, using location information from the world model and the laser ranging subsystem. A single video cable carries the composite color signal from the vehicle to the Unix workstation. Video signals are decoded into Red, Green and Blue images prior to digitization on the Androx framegrabber. Vision software runs under control of the system executive, and as soon as the current image is digitized, the scan platform and vehicle are released to perform other tasks while the image is processed off-line. We prepared samples of rust, rust streaks and corroded paint on black and white drums for developing and testing the vision software.

Image analysis algorithms are developed on a Unix workstation using the Khoros image processing package with pattern recognition tools from our neural network IR&D. Optimized versions of the image processing software will run directly on the framegrabber board instead of on a workstation. Figure 18 illustrates the image analysis process. A smoothing filter is first applied to the input RGB image to eliminate noise and reduce sharp edges (RGB color edges are not well defined, and are not used here). Prior to feature extraction the RGB tristimulus response images are orthogonalized (decorrelated) by transforming into the Ohta color space, which is a fast approximation to the Karhunen-Loeve eigenvector transform [Ohta]. The new image bands are "intensity" = $(r + g + b)/3$, "red - blue difference" = $r - b$, and "excess green" = $(2g - r - b)/2$. Figure 19 illustrates input RGB and transformed image bands for a black drum (a rust patch appears in the lower left-hand corner).

A model-based vision approach is used, wherein the drum color is first determined (by inspection or from world model), and then separate modules (with color-dependent parameters) identify rust, streaks and corrosion. Even though rust spots on different drums appear similar to human vision, color computer vision must proceed with RGB images as the starting point. For example, a small rust spot in the red image from a white drum has mean intensity of 45 and standard deviation of 4.8, while a similar rust spot in the red image from a black drum has mean of 92 and standard deviation of 8.5. Since both rust spots were produced in the same way, the spectral difference is due to different contrast from the surrounding paint. Drum color is determined by a maximum likelihood threshold detector [Pratt] on centered subimages. Based on the selected color model, adaptive and multispectral histogram thresholding is performed to develop binary image masks.

Streak detection is performed separately from rust and corrosion detection. Even though spectral information is important for finding streaks, the dominant feature is shape (narrow, tapered vertical streaks of variable intensity). The thresholding process produces a binary image that includes any potential streak structure, and morphological shape filters [Haralick] are iteratively applied to identify extended streaks caused by rust or leaks. Streak detection results (a segmented image) are sent to the analysis module for reporting.

Features corresponding to rust and corrosion are extracted from the transformed input images. Microfeatures include statistics (mean and standard deviation) and texture (entropy and homogeneity) on small windows (5x5). Macrofeatures include variance and Singular Value Decomposition eigenvalues [Pratt] on larger windows (15x15) from the textured images. Feature values are combined into a feature vector (1 vector per pixel). Each pixel is then labeled according to its class membership (rust, corrosion, labels, paint) using a supervised clustering algorithm, with color specific parameters (distance measures). It is relatively easy to hand-tune parameters at the computer console to detect rust or corrosion in a particular image. It is more difficult to determine parameter ranges for robust, autonomous inspection outside of the lab. Hence, supervised clustering methods for pattern recognition (e.g., k-means [Coleman] or Learning Vector Quantization [Visa]) can be used in the general case. Feature values from the Ohta color space were used directly to discriminate rust in Phase I tests. The result of feature extraction and classification is a segmented image with regions of interest labeled. The analysis module quantifies detected anomalies (rust, corrosion, missing paint, and streaks) for reporting.

Figure 18 - Block Diagram of Image Analysis Process

a. *d.* *b.* *e.* *c.* *f.*

Figure 19 - Transforming RGB to Ohta Color Space.
A sample 3-band input image is shown on the left [a) Red, b) Green and c) Blue] with the transformed image on the right [d) Intensity, e) Blue - Red and f) Excess Green].

5.1.6.3 Bar Code Scanner

Bar code labels are used to identify and track waste storage drums. For autonomous label scanning the Phase I IMSS vehicle employs a Symbol Technologies Laserscan 6120 visible laser diode scanner. This laser operates at 680nm with 1.0mW max power and is a Class IIa laser (no special precautions needed, other than to avoid staring into the light beam). Power is supplied by the vehicle, and an RS-232 cable connects the scanner to a Unix workstation for computer control. The scanner is physically located on an extension boom attached to the side of the vehicle pan-tilt platform. The demonstration uses bar code labels similar to the supplied samples (1" tall vertical bars, medium density, Code 3 of 9 symbols, with 10 alpha-numeric characters). The Phase II scanner will be able to read smaller labels at larger distances.

For nominal weekly inspections the bar code label location on the drum is known from the world model. For new drums or anomalous situations the label can be located using shape analysis of thresholded images from the color camera. The vehicle is commanded to move the scanner into location for reading the label (by moving the pan-tilt platform or repositioning the vehicle if necessary). Preliminary testing shows the scanner consistently reads labels from 30cm distance and ± 25 degrees in any direction. A "Laser-On" command from the computer turns on the scanner and an ASCII string is returned on a successful read. The laser automatically turns off after a successful read, or after 1 second, whichever comes first. The laser can be in motion while scanning. The bar code software module is controlled by the system executive.

5.1.7. Executive

5.1.7.1. Purpose of the Mission Executive

The purpose of the Mission Executive is to direct the integrated action of the various functions of the vehicle to achieve an efficient and complete inspection of the site (Figure 20). The functions controlled by this module include the mobility and scan platforms, some parameter setting on the vehicle, the structured light 3D vision module, the color vision module, the visual landmark navigation module, and the bar code reader. The details of how the functions are performed are left to each of the individual sensor or motor modules (e.g. a "rust inspection" command may be issued by the mission executive to the color vision module, but the details of how that is performed are left to that module). Since some of these modules can change the state of the vehicle (e.g. scan platform location, hardware configuration), the mission executive also receives or requests relevant information pertaining to these state changes in order to coordinate the remaining action effectively.

Efficient inspection is achieved in two ways. First, inspection sequences which minimize changes in vehicle state and position will be efficient relative to those that don't. Second, maximizing concurrency of task performance will tend to minimize inspection time.

5.1.7.2. Functions of the Mission Executive

The functions entailed in this module include initial plan generation, plan dispatching and monitoring, and real time plan adjustments.

5.1.7.2.A) Initial Plan Generation. This function generates a plan of action consisting of integrated mobility and scan platform motions, and various sensing operations¹. The plan is based on the site information provided in the world model, and the costs and constraints associated with each potential action. Operations research and heuristic algorithms can use this information to generate a complete and efficient plan for the site inspection.

Because this module has a complete model of a relatively stable environment with fixed task requirements, a high degree of efficiency can be achieved using global optimization strategies, rather than following local or reactive planning techniques. The global perspective also provides assurance that a complete inspection will

¹ Sensors that are used to constantly monitor conditions, with invariant demands on vehicle resources and no effect on vehicle action (e.g. gas sniffers and radiation monitors) need not be interfaced to the executive. The contact sensors (soft bumpers), which are passive monitors do, however, affect vehicle motion. The effects of this system must be monitored and used to adjust the actions of the vehicle in real time. However, the executive does not control these sensors.

be performed. Minor perturbations in the actual environment can be accommodated by following local plan repair strategies, as discussed below, without significant impact on the overall efficiency of the plan. Strategies in initial plan generation can be used both to minimize state changes and to maximize concurrent performance of operations, thus maximizing the efficiency of the performed inspection sequence.

Minimizing state changes.

Any state change that takes time or energy should be minimized. Of course, some state changes have a larger impact on time than others. Vehicle and scan platform motion are the largest sources of time consumption and energy usage for state changes. The least impact on time is turning the lamp on and off (some sensors perform better with the lamp on, others with it off).² An intermediate source of time and energy usage is the use of a single processing board by two separate sensor systems. To share this board, these systems must be attached and detached, which involves some synchronization which can take a second or two. It is the responsibility of the Plan Generator to create a plan which minimizes these state changes.

State changes are minimized by using the following heuristics:

- direct a single vehicle motion that can position the vehicle to perform multiple sensor readings
- minimize pan & tilt moves by sequencing sensor acquisition commands where sensor operation N ends its operation in a scan position close to the second sensor operation N+1's required position.
- group actions that require the same state (e.g. lamp on, or processor board attachment)

Maximizing concurrent task performance.

Interruptions in inspection sequences can be minimized by predicting likely potential overlaps and grouping actions that could potentially overlap together. The groupings that save the most time are those that allow data processing operations for one sensor module to occur while other vehicle and scan motions, or other sensor data collection are occurring. For example, the final stages of data processing, after data collection, for the laser 3D imaging can take about 21 seconds. If two laser 3D imaging tasks are commanded back to back, the inspection will be halted for 21 seconds while the processing for the first task is completed, before the laser imaging system will take another command. However this processing can take place when the vehicle is in motion, or other sensors are collecting and processing their data, so a 21 second time savings per drum can be realized if actions are properly ordered.

A simple algorithm was used in phase 1 to generate efficient plans. Each drum was inspected from one vehicle position, which minimized required vehicle and scan platform motion. For each vehicle position one stack of drums to the left and one stack of drums to the right was inspectable. From a given position, each drum was completely inspected before the next one was begun, minimizing movements of the scan platform. The order of drums inspected, left to right and top to bottom, was determined by the previous position of the scan platform, to minimize motion of the platform. E.g. if in the last drum inspected from position 2 was the top left drum, and the scan platform completed the last sensor operation pointing to the top of the drum, then from position 3 the drum inspection sequence would be 1) top left (starting from top), 2) bottom left (from top), 3) bottom right ...

The order of sensor operations for an individual barrel was determined by sensor mast orientation and potential processing overlap with other actions. Landmark acquisition orders were determined by a combination of the sensor platform position from the previous operation, the desired position for the subsequent operation, and the potential of overlapping landmark processing for an individual landmark with the acquisition of position for the next landmark. This algorithm was implemented manually. For phase 2 a more flexible algorithm, which can generate optimal plans for diverse operational scenarios, will be devised and implemented.

5.1.7.2.B) Plan Dispatching & Monitoring. Employing the plan constructed by the previous module, commands are issued to each function at the appropriate time, and the progress of each function is monitored

² Effects on energy usage for the current lamp have not been determined, but will be factored into efficiency in phase 2.

to maintain a coordinated inspection sequence. The most efficient operation of the vehicle will entail concurrent performance of compatible operations. However, many of the functions are either directly or indirectly incompatible, so the coordination function in this module can be fairly complex.

Concurrency without chaos. By overlapping actions where possible, significant time savings can be achieved in the inspection sequence. The most profitable of these are overlapping vehicle and scan platform motion, overlapping image processing with any other vehicle or sensor activity, and anticipatory state changes, particularly changing the attachment of the processing board that was used by two of the sensor systems. However, not all actions can occur concurrently, and ordering of actions - both concurrent and sequential - must be carefully controlled. The plan provided by the Plan Monitor sets up an ordering that allows the dispatcher to take advantage of the most profitable concurrencies. The dispatcher uses that plan to generate coordinated action sequences that achieve complete, efficient inspections.

This is achieved through the use of ordered command queues, monitoring of the state of the vehicle and the progress of each of the commanded modules, and checking of the required states for each of the pending commands.

There are three main command queues - Pending, In Progress, and Complete. The Pending command queue contains an ordered list of the next n operations³ on the plan command list⁴ that have not yet been initiated. The In Progress queue contains a list of all commands currently being executed and their status. The Complete queue contains a list of all commands that have been fully executed and their final disposition, ordered by completion time.

Two types of state variables were tracked during execution for each of the vehicle and sensor components. One set tracked the actual state of the component (e.g. LAMP might be set to ON or OFF), and the other set tracked which component had the right to change state of a given component/module (e.g. the SATURN_ANDROX_BOARD control might be set to FREE_CONTROL or STEREO_CONTROL or LANDMARK_CONTROL).

To coordinate concurrent operations, the following procedure was followed:

For each of the modules (sensor and vehicle) a communications channel was established to allow commanding and status tracking. To initiate inspection, the pending queue was filled from the plan generated by the Plan Generator.

Until all commands have been executed:

- 1) Poll Communications: Until communications queues are empty:
 - a) Poll sensor and vehicle communications ports to check for incoming messages.
 - b) Interpret incoming message
 - c) Change state and control variables according to message received
 - d) Update In Progress and Completed queues as appropriate.
- 2) Update Pending queue: Until a command in Pending queue can be executed or end of Pending queue is reached, for each item:
 - a) Check to see if states required for command are true

³ On most test runs, the Pending queue had a length of 5.

⁴ Actually, the dispatcher would also push onto the list any required precursor command for a given operation. So, for instance, the rust detection sensor operations required a lamp to be on before data collection. A LAMP_ON command was pushed onto the pending list before the color command.

- b) Claim control for any variable that is necessary for this command
- c) If all states are true and all required control is achieved,
 - i) execute command
 - ii) set new states as required
 - iii) move command from Pending to In Progress queue

3) Fill Pending queue.

By carefully monitoring the current state and control of each variable, a determination can be made of what commands may and may not be concurrently executed. By setting control variables for each of the modules, ordering of commands is achieved when necessary, since any conflicting requirements are resolved in favor of the earliest item on the Pending queue.

5.1.7.2.C) Real Time Plan Adjustment - Reactive Replanning and Plan Refinement. Although true excursions from the expected environment should occur only very rarely at these sites, when these anomalies do arise, the system must be fully competent to handle these anomalies and proceed with the inspection process. The replanning functions alter or refine the plan as the inspection sequence progresses to adjust to real-time inputs during the inspection procedure. Such inputs include anomalies such as discrepancies between actual and expected observations (e.g. drums out of place, missing bar codes), and the detection of a faulty drum. These functions rely primarily on local repair heuristics, since most of the effects of excursions from the expected environment are local in nature, and do not significantly interact with the overall plan. For instance, if a barrel is found slightly out of place, there are local effects on what should occur in the inspection sequence at that location, but the rest of the inspection sequence is still valid. In this case, a new short sequence of motion, sensing and recording actions can be introduced, to find the exact location of the drum, inspect the drum in this newly found location, and to create a flag to report the anomalous position to the world model. The system will then return to following the initial plan as specified. A number of different heuristic repair strategies are required to handle the diverse types of contingencies that may be encountered or plan refinements that may be required. Under some sensor failure conditions, the vehicle simply continues the inspection sequence. Under many conditions, however, new actions must be planned and performed.

Included in these replanning functions are procedures to return the vehicle to a safe and recoverable state/location in the case of serious vehicle or environment problems. These will consist of generation of a new, simple plan to return home given knowledge of current location and home, and also a strategy that allows the vehicle to search for home using local decision-making strategies that guarantee an efficient exhaustive search of the physical site. A subset of these repair and refinement strategies are implemented in the current phase. They were not tested due to limitations of the current soft bumper hardware.⁵ A study of strategies that return the vehicle to safe in catastrophic situations was initiated in phase one. Design and implementation will be completed in phase two.

⁵ The only algorithms implemented involved renavigation on blocking conditions. Because the ultrasonic sensors did not provide complete coverage for collision avoidance, and caused the vehicle to navigate peculiarly in tight situations, it was not possible to do any real testing of obstacle avoidance behavior.

Figure 20 - Interfaces to the Mission Executive.

The mission executive consists of three modules: Plan Generator, Plan Dispatcher and Monitor, and Reactive Replanner. The Plan Generator creates a plan before the inspection is begun. This plan is handed off to the Dispatcher. The Dispatcher issues commands to the sensory and motor modules, and receives feedback from them regarding their progress. The Replanner is called when certain anomalies occur, and provides a plan repair to be followed by the Dispatcher. All sensor modules except the Bar Code Reader access the World Model for information regarding the site and drum characteristics.

5.1.8. Operator Interface

The IMSS operator interface allows the storage facility operator to direct and review the inspection process. The phase one operator interface includes both operational and developmental capabilities. The developmental capabilities are described in the section on vehicle control, and operational capabilities are described in the section on task assignment. The third section describes the database for facility information and inspection reporting.

5.1.8.1. Vehicle Operation

The vehicle control interface is based on a graphical touch screen interface. This graphical interface was previously developed under internal funding for robotic control applications [Morgenthaller]. The following sections describe the individual screens supporting the vehicle and sensor control functions. Command buttons which allow the operator to switch between menu screens appear on every screen and are

described in Table VI. The button associated with the current screen is highlighted in color (violet) to identify the active screen. These buttons do not activate functions, they merely switch menu screens.

Table VI - Menu Screen Selection Buttons

Button Function	Action Description
Mission executive menu screen	Switch to the MISSION EXECUTIVE menu screen.
Facility layout menu screen	Switch to the FACILITY LAYOUT menu screen.
Rover teleoperation menu screen	Switch to the ROVER TELEOPERATION menu screen.
Vehicle control menu screen	Switch to the VEHICLE CONTROL menu screen.
Scan platform control menu screen	Switch to the SCAN CONTROL menu screen.
Sensor menu screen	Switch to the SENSOR menu screen.
Data display menu screen	Switch to the DATA DISPLAY menu screen.

Vehicle Control Screen—This screen provides the user control of the vehicle mobility. A print of this screen is included in Appendix B. Command buttons for this menu screen are described in Table VII.

Scan Platform Control Screen—This screen provides the user control of the scan platform. A print of this screen is included in Appendix B. Command buttons for this menu screen are described in Table VIII.

Data Display Screen—This screen provides the user real-time data displays.

Sensor Operation Screen—This screen provides the user control of the mission sensors.

5.1.8.2. Task Assignment

The task assignment interface uses the same graphical touch screen format as the vehicle control interface. The task assignment functions allow the user to operate the mission executive, and plan and monitor using the facility map.

Mission Executive Screen—This screen provides the user control of the mission sensors and is used to initiate an inspection mission. It also provides windows that give a "history script" of an inspection mission and an abbreviated list of defects that were reported.

Facility Layout Screen—This screen provides the user map-based mission planning and monitoring. A print of this screen is included in Appendix B. This screen is a scaled display, as viewed from overhead, of the facility data as loaded from the facility model (described in the Database section). Drums are displayed as circular buttons which the user can select for inspection. When a drum is reported as defective, the corresponding drum button on this screen is highlighted in red to flag the operator. Other geometric information is also displayed to scale: Facility boundaries, aisles, obstacles, and landmarks. Each category of object is presented in a different color and tagged with an index number for discrimination. The vehicle position data display is used with this screen to display the vehicle position trail. The current vehicle position and scan platform direction is also shown if the vehicle is in communication with the operator interface.

Table VII - Vehicle Control Screen Buttons

Button Function	Action Description
Enable move to location action	Sets the action flag to MOVE, changing the function of the vehicle location action buttons to cause execution of the trajectory move. Sets the verify flag on those buttons, consistent with commands causing motion. Resets the default color on all location action buttons.
Enable select edit location action	Sets the action flag to EDIT, changing the function of the vehicle location action buttons to cause selection of the location for editing. Clears the verify flag on those buttons.
Location V1...V12 actions	This applies to all twelve vehicle location action buttons. They check the state of the action flag: (a) If MOVE, issues an absolute trajectory command to the set of Cartesian values specified by this location. In this mode, this button is verified; (b) If EDIT, copies the location data into the edit area and flags this location to receive edit updates. Also updates the default location button's color to indicate selection and resets the others.
Move to current edit location	Issues an absolute Cartesian trajectory command to the specified set of Cartesian values in the edit area for the selected location. This button is verified.
Set location to current Cartesian pose	Requests Cartesian position data from the data receiver. Sets the edit location's Cartesian values to the <u>measured</u> values returned by the controller.
Assign name to location	Prompts the user with a text entry tool for a name of this location. The name can be one or two lines of up to ten characters each, with embedded spaces allowed. The following characters are allowed (A-Z,a-z,0-9,space). If two lines are entered, they are separated on the input line by a period (.). Examples: "Home loc", "Home.Location". The name is used on the location action button, and is saved along with the rest of the location data.
Enter X displacement	Prompts the user with the numeric entry tool for a new value. The units used are set with the Cartesian displacement unit button. The value entered is displayed on the button and copied into the selected location's data area.
Enter Y displacement	Prompts the user with the numeric entry tool for a new value. The units used are set with the Cartesian displacement unit button. The value entered is displayed on the button and copied into the selected location's data area.
Enter orientation angle	Prompts the user with the numeric entry tool for a new value. The units used are set with the Cartesian angle unit button. The value entered is displayed on the button and copied into the selected location's data area.
Halt vehicle trajectory motion	Suspends execution of current trajectory by sending an abort command to the vehicle controller. Has no effect if the vehicle is not performing a trajectory. Leaves the control system ready for any subsequent command.
Save vehicle locations to file	Save the Cartesian location library to a disk file. The file name is entered with the text tool. The joint values and name are saved for each of the eight locations. This file is plain text in a format similar to the button screen definition file, and can be modified with a text editor.
Load vehicle locations from file	Load the Cartesian location library from a disk file. The file name is entered with the text tool. The joint values and name are loaded for each of the eight locations.
Change Cartesian position units	Change units used by all displays and entry tools for Cartesian displacements between inches, feet, meters, and centimeters.
Change Cartesian orientation units	Change units used by all displays and entry tools for Cartesian rotations between radians and degrees.
Update vehicle controller current Cartesian position	Prompts the user with the numeric entry tool for the new X,Y, and yaw values. Downloads new reference Cartesian position data to the vehicle controller. This has the same effect as a landmark-based position update. Any pending vehicle motion commands are aborted.
Teleoperate vehicle from hand controller	Commands direct transfer of hand controller data to the vehicle controller as velocity commands. This is a toggle, a subsequent command will turn teleoperation off. Disables scan platform teleoperation, if existing.

Table VIII - Scan Platform Control Screen Buttons

Button Function	Action Description
Enable move to location action	Sets the action flag to MOVE, changing the function of the scan platform location action buttons to cause execution of the trajectory move. Sets the verify flag on those buttons, consistent with commands causing motion. Resets the default color on all location action buttons.
Enable select edit location action	Sets the action flag to EDIT, changing the function of the scan platform location action buttons to cause selection of the location for editing. Clears the verify flag on those buttons.
Location S1...S12 actions	This applies to all twelve scan platform location action buttons. They check the state of the action flag: (a) If MOVE, issues an absolute trajectory command to the set of joint space values specified by this location. In this mode, this button is verified; (b) If EDIT, copies the location data into the edit area and flags this location to receive edit updates. Also updates the default location button's color to indicate selection and resets the others.
Move to current edit location	Issues an absolute joint space trajectory command to the specified set of joint space values in the edit area for the selected location. This button is verified.
Set location to current pose	Requests scan platform joint space position data from the data receiver. Sets the edit location's joint space values to the <u>measured</u> values returned by the controller.
Assign name to location	Prompts the user with a text entry tool for a name of this location. The name can be one or two lines of up to ten characters each, with embedded spaces allowed. The following characters are allowed (A-Z,a-z,0-9,space). If two lines are entered, they are separated on the input line by a period (.). Examples: "Home loc", "Home.Location". The name is used on the location action button, and is saved along with the rest of the location data.
Enter scan platform pan (yaw) angle	Prompts the user with the numeric entry tool for a new value. The units used are set with the joint space angle unit button. The value entered is displayed on the button and copied into the selected location's data area.
Enter scan platform tilt (pitch) angle	Prompts the user with the numeric entry tool for a new value. The units used are set with the joint space angle unit button. The value entered is displayed on the button and copied into the selected location's data area.
Halt scan platform trajectory motion	Suspends execution of current trajectory by sending an abort command to the scan platform controller. Has no effect if the scan platform is not performing a trajectory. Leaves the control system ready for any subsequent command.
Save scan platform locations to file	Save the joint space scan platform location library to a disk file. The file name is entered with the text tool. The joint values and name are saved for each of the eight locations. This file is plain text in a format similar to the button screen definition file, and can be modified with a text editor.
Load Cartesian locations from file	Load the joint space scan platform location library from a disk file. The file name is entered with the text tool. The joint values and name are loaded for each of the eight locations.
Change joint space orientation units	Change units used by all displays and entry tools for joint space rotations between radians and degrees.
Teleoperate scan platform from hand control	Commands direct transfer of hand controller data to the scan platform controller as velocity commands. This is a toggle, a subsequent command will turn teleoperation off. Disables vehicle teleoperation, if existing.

5.1.8.3. Reporting Data Base

The IMSS database consists of two major data sets: the facility model, and the reporting database. The facility model contains information about the fixed components of the facility, things which are not expected to change. Examples of facility model data include drum locations, aisle endpoints, obstacle locations and sizes, landmark locations, and basic drum geometry. Figure 21 shows the drum coordinate frame definitions. This data is used for mission planning and execution monitoring. The facility model is accessed by all other processes other than the vehicle controller. It is only updated under control of the operator interface to maintain integrity.

The reporting database contains information resulting from the inspection process. Examples of reporting database data include missing drums, rust patches, and dents. Such defects are indexed by the drum from the facility model on which they were identified. The reporting database is updated by sensor processes and the mission executive. Data is read out to the mission executive and the operator interface. The database was implemented as a server process on a Unix workstation. Tables of commands and data structures for the IMSS database are located in Appendix A. The code is standard C and can be readily ported to another platform. The network interface was implemented with the project-standard TCP/IP library.

Figure 21 - Drum Model Definitions

5.1.9. Safety System

Vehicle and scan platform motion may be aborted either via software command or kill switch actuation. The two abort modes differ significantly.

5.1.9.1. Software Aborts

When the wheel or scan platform control task receives a software abort, any current motion is immediately terminated and the task command queue is cleared. However, both tasks remain active and subsequent commands will be executed upon reception. This abort mode does not affect the hardware other than terminating motion.

5.1.9.2. Manual Aborts

A manual abort is initiated by the actuation of a tether mounted kill switch. Actuation of this switch disables the wheel, pan, and tilt motor amplifiers and is announced to the software by a digital discrete. When a manual abort is detected by the software, all wheel and scan platform control commands are rejected pending the receipt of a specific enabling command. The enabling command will be rejected while the kill switch is active. This command can only be initiated by the system operator interface, therefore a manual input is required to re-enable the vehicle following a manual abort.

5.1.9.3. Power Up State

The vehicle will be in manual abort mode at power up. Both a software controlled digital discrete and deactivation of the kill switch are required to initially enable the vehicle. Software control of the manual abort signal is not used at any time other than power up. A manual abort will be issued by kill switch activation regardless of the state of the software controlled discrete.

5.2. Test Facility

5.2.1. Waste Storage Facility (WSF) Mockup

The test facility was configured inside a truckwell. The enclosed area is approximately 5.5m x 9.5m and is 5m high. This area was chosen because it had characteristics similar to many of the current DOE storage facilities. The floor was concrete with some seams and some patches. The lighting consists of six incandescent bulbs providing a somewhat dim environment. Other DOE storage facilities range from relatively bright halogen systems to fluorescent systems to incandescent. Our test facility was in the lower end of the brightness scale providing a worst case environment for development.

The test setup is diagrammed in Figure 22. It is composed of three rows of drums with two aisles, a back aisle and a staging area. The outer rows of drums along the walls of the truckwell were stacked two high. These were secured to the wall for safety. The center row was one stack high. This was because the truckwell was active during the testing phase and trucks and equipment had to move through the area. Thus the center row of barrels were frequently moved into and out of position. Some known obstacles were present in the test area including a column and some liquid nitrogen tanks.

Figure 22 - Diagram of Test Facility

5.2.2. Experiment Preparation

The barrels that were installed in the test facility were new waste drums that had not been used before. This was to satisfy environmental and safety requirements. Note however that "new" does not necessarily mean pristine, it means not yet used for waste storage. Many of the drums had evidently been in open storage for some time. A total of 38 drums were located in the facility including 55 gallon and 87 gallon sizes. Colors included black, yellow, white, and silver (stainless steel). Barrel quality ranged from freshly painted to having a somewhat heavy spread of lightly rusted nicks and scratches. Many drums had mud and dirt on the outer surface.

A range of labels were added to the drums to make them more realistic. Labels included some stenciled numbers and letters, various official DOE labels including hazardous waste labels, and local annotations like orange tape with handwritten numbers such as used by Rocky Flats to update radiation levels as measured weekly.

A range of defects were added to a subset of the drums. Added defects included rust, rust streaks, corrosion, and dents. Rust was added by filing or scratching various sized areas on certain barrels. These bare metal patches were then repeatedly sprayed with salt water over the course of several weeks. Rust patch size varied from large 30cm² patches to pea sized areas. Rust streaks were created on some drums by applying larger and more frequent amounts of salt water. Corrosion was simulated by applying paint remover in various locations while varying the concentration and duration of application. Dents were added to several barrels with methods ranging from using a hammer to using a very large rock. Dent depths ranged from 1cm to 8cm.

All drums were marked with a barcode. We conformed to current DOE specifications obtained from some sample barcodes. The barcodes were 2cm x 5cm and followed code 39 specifications. The labels were oriented with the bars in the vertical direction ("picket fence"). We implemented our own numbering scheme which was tied into our site database and reporting database (cf. §5.1.8.3 and §5.4.7.3). Each barcode was located in the upper third of the drum and was oriented to approximately face outward.

5.2.3. Operational Scenario

Physically, the vehicle operated in a tethered mode, mainly for ease of development. The vision processing, navigation and reporting processes were all run offboard on separate engineering workstations (cf. §5.3.1.). This allowed parallel development and more powerful development tools without continuously downloading code to the vehicle. The migration of computing to the vehicle will occur during the next phase when the software requirements have firmed up and are changing less. Also, this allowed us to begin integrated testing earlier and with less schedule risk. The tether also contained a power line although this was not strictly necessary since there were on board batteries.

Operationally, the scenario was setup to emulate a reasonable inspection process that would be acceptable to any user group. The drums were placed in areas of the floor called drum rows. Drums are assumed to be completely within the drum rows (for planner purposes). There is a small amount of free space in the drum rows not occupied by the drums (ie. the drum row is wider than the drums, and is longer than the sum of the length of the drums). In between the drum rows is space for the vehicle to move, called (traversability) aisles.

Assumptions used in this scenario included:

- System has an a priori map of the WSF. The map contains an exact representation of the WSF, specifically the location of the walls, doors, and any known obstructions. It also has a good representation of the location of the drum aisles.
- The locations of the drums within the drum aisles is not known, only that they are within the drum rows. We also know the (presumed) number of drums in each row.
- Landmarks or fiducial markings are placed in strategic places on the walls. The positions of these are known within the room.

The nominal inspection scenario goes as follows:

- The vehicle begins its mission at the entrance to the storage area at its recharge/data site (operator console).
- Navigation sensors look around for landmarks and report the location and orientation of the vehicle. This function is executed periodically (at the end of each aisle) throughout the mission. The vehicle is stopped while the position update process occurs. This allows the sensors to acquire their information and process it allowing for camera pan/tilt motions and lens zoom, as well as allowing for updating the vehicle world position before resuming motion.
- The vehicle moves to a position in front of the first (next) traversability aisle and locates the first drum.
- The vehicle moves to the inspection position centered relative to the drum. Parametric testing showed that sensing from one centered position is obviously much more efficient than taking

multiple views from each exposed side of the drum, without losing significant information on the visible edges of the drums.

- At given inspection positions, the sensing system will scan the drum with its laser striper and/or acquire a color digital image. Each sensor needs multiple views per drum (two swaths for laser striper, and three images for color camera). Dent detection with the laser striper requires the vehicle to be stationary and the sensor mast to scan through (approximately) 20°. The acquired data from the two black and white cameras is subsequently fused during other system sensing or motion processes. The color digital image must be acquired while the vehicle is stopped and is used for the other detection processes (cf. §5.1.6.2.). Processing of the images may occur during other vehicle activity.
- The vehicle continues down the aisle stopping periodically to inspect drums.
- The laser striper and camera light are turned off when not in use to conserve power.
- At the end of the aisle, the vehicle must reverse its direction or go to the next aisle. This is a function of the planned path which is mainly a function of the facility topography.
- When all drums have been inspected, the vehicle returns to its starting point. A report on its findings is created and displayed on the operators terminal.

5.3. Engineering Development Environment

5.3.1. Software Environment

The vehicle software was developed on a network of engineering workstations. This allowed parallel development of the different software modules without any resource bottlenecks as well as avoiding the immediate cost of fitting all the software onto the vehicle computers. Nine workstations were linked over a local ethernet (Figure 23) that could be attached to the company backbone when necessary. Workstations included three IRIS's, three SUN IV's, a Symbolics, and two SPARC IPC's. One of the SPARC IPC's served as the gateway to the vehicle computing environment.

Figure 23 - Software Development Environment

5.3.2. Video Environment

Actual pictures of good and bad barrels from DOE storage facilities were used to develop and train the vision algorithms. These were supplemented with images from our local test facility mockup.

Image analysis development work was performed on a SPARC II workstation using Khoros software and a neural network training system.

For onsite verification of the visual sensing modules, images of the camera were sent through a video switching unit to the workstation. The workstation was tied into the rest of the software development effort by the environment described in Section 5.3.1.

5.3.3. Hardware Prototyping and Testing

The integration effort was conducted within our main laboratory space (about 10m x 10m). This area included the real-time development system, an ethernet repeater, and electronic test equipment as well as the vehicle and some barrels. Initial test and checkout were performed on blocks and on the floor in this area. Required metalwork was performed on small machines in a nearby room. Electronics bread boarding, cabling, and packaging were performed in a nearby room to a strict level of quality.

5.4. Parametric Performance Measurements

The purpose of phase one is to provide data for the subsequent design of a robust, cost effective, appropriately sized prototype system. As such it is important to know where performance margins are needed for robustness, where performance margins are available from equipment, and where the subsystems interact to perform the required functions. Various measurements were taken of actual system performance both overall and for different aspects of particular components or subsystems. The parameters of interest and the method of measuring them are discussed below. Conclusions from the performance data and a discussion of their impact on the phase two prototype are discussed in Section 6.

5.4.1. Mechanical Subsystems

5.4.1.1. Motion Platform

All mechanical elements of the vehicle motion control system were already tested and functional when vehicle was delivered from the Mars Rover Program. No additional testing was required.

5.4.1.2. Sensor Platform

5.4.2. Electrical Subsystems

5.4.2.1. Vehicle Electronics

The control electronics were functionally tested. Functional testing included proper execution of required system functions, such as software execution, response to motor commands, power state control, and others. No parametric testing was performed.

5.4.2.2. Ultrasonic Transducers

The ultrasonic transducers were functionally tested. No parametric testing was performed, largely because we know that the current system is inadequate for a satisfactory collision avoidance system. This system was used to show proof of concept and to provide inputs to test the collision avoidance kinematics.

5.4.2.3. Communications

The network communications performed nominally during phase one. The laboratory network was disconnected from the MMAG network backbone during operations to eliminate potential Ethernet data collisions from other users. This network is only used for Phase I development.

5.4.2.4. Power

The power system was functionally tested. No parametric testing was performed.

5.4.3. Control

Testing of the onboard control systems is a two stage process. Initial tests established control system parameters for reasonable performance given the constraints of the controller implementation. Final testing characterized vehicle performance at a functional level.

5.4.3.1. Vehicle

The important vehicle position control subsystem performance issues that affect system level operation are cartesian positioning accuracy and actual position knowledge accuracy. Factors affecting position control and position knowledge are:

- Wheel controller velocity following accuracy
- Vehicle and wheel kinematic parameter knowledge
- Wheel slippage

Wheel velocity following error can be minimized by measuring velocity error and adjusting the motion controller position loop PID gains to maximize loop bandwidth while maintaining a well behaved dynamic response. Accurate measurement of wheel diameters and wheel location with respect to the vehicle reference coordinate frame will minimize errors resulting from kinematic transformations. Wheel slippage is dependent on the running surface, wheel roller irregularities, and roller deformation so will not be controllable.

Absolute vehicle positioning error was measured on the test floor for point to point and closed circuit moves.

Accuracy of vehicle position knowledge obtained from odometry was also be measured. These accuracy measurements determine how frequently landmark targets will be required to update vehicle position.

5.4.3.2. Obstacle Avoidance

The collision avoidance mechanism is integrated into the vehicle position control architecture and therefore interacts dynamically with it. Therefore, initial parameter selection and testing was conducted with the vehicle in the loop. Collision avoidance is essentially an outer cartesian control loop closed around the vehicle operating on relative vehicle position and producing vehicle velocity commands. Testing initially focused on determining the proper form for the virtual force filter and the impedance filter of Figure 10 to ensure good sensitivity and speed of response to obstacles while at the same time providing unconditional stability.

Ultrasonic sensor update rate limitations restrict sample rates for the collision avoidance loop to less than 10 hz. A sampling rate this low will degrade stability, therefore special attention was given to the form of this loop to guarantee stability and robustness.

Impedance Filter

A heuristic approach to impedance filter implementation suggests several possible forms. A mechanical damper model results in a proportional relationship between force and velocity ($1/b$) where b is the damper constant. This form implies a constant velocity vehicle response from a constant virtual force developed by an obstacle. This is the simplest form, adding no additional dynamics to the loop and is likely to be the most robust in terms of satisfying the unconditional stability requirement. A second approach models a mechanical mass-damper and results in a 1st order relationship between force and velocity ($1/(ms+b)$) where m is mass/inertia and b is again the damping constant. This relationship results in a vehicle velocity response that grows with a time constant of m/b . This approach offers the ability to adjust the speed of response to an obstacle separately from sensitivity. However, because the impedance filter adds dynamics and increases the system pole-zero excess, unconditional stability may be more difficult to ensure. The simple mechanical damper model approach was tested first

Virtual Force Filter

The proposed inverse square law force potential is nonlinear and results in larger and larger loop gain as range to an obstacle decreases. This can result in stability difficulties when operating in confined spaces (barrels close to opposite sides of the vehicle). Tests with the vehicle confined tightly on all sides were conducted to determine the best implementation of this filter.

5.4.3.3. Scan Platform

Pan and Tilt Controller Adjustment

Motion control PID parameters were adjusted when the full platform inertia load was present. To track scan moves of 10 degree per second a bandwidth of at least 1-2 hz should be configured with sufficient integrator gain to limit constant velocity tracking error to approximately 0.5 degree. The gain adjustments necessary can best be accomplished by using the following procedure:

- 1) set the ratio of proportional to integral gain in the Galil controller equal to 1 hz and set the integral equal to 0
- 2) increase the loop gain until an overdamped time response is observed while commanding small position change commands
- 3) increase the integral gain until the time response exhibits slight overshoot

Pan and Tilt Alignment

Zero pan and tilt angles should align the scan platform coordinate frame with the vehicle reference coordinate frame. This would, for example, point the LASER striper straight ahead along the vehicle reference coordinate frame x-axis. The following procedure was used to determine initial alignment location:

- 1) register vehicle front surface against a vertical plane (wall)
- 2) home the pan and tilt axis to the encoder index pulse
- 3) using a mirror on the wall, reflect light from the LASER striper back towards the source
- 4) adjust pan and tilt angles until the LASER beam is reflected back to the source
- 5) the offset angles from the home position to the aligned position should be recorded and used to establish the zero pan and tilt location after homing to the index pulse

5.4.4. Navigation

The overall navigation system performance is a function of the two methods used: wheel odometry and landmark sightings. Errors in odometry (dead reckoning) are compensated for by landmark sightings, at the expense of the time required to acquire and process the data. Performance results for the individual methods is given below, followed by results for the combined navigation system.

5.4.4.1 Wheel Odometry

The technique for determining the odometry performance was to characterize motion in each vehicle axis separately first, then a representative inspection motion sequence using all axes. The floor surface used for this characterization was the same as the demonstration area: sealed concrete.

Forward translation—The vehicle was commanded to translate forwards and stop. The distances and measurements are shown in Table IX.

Table IX - Forward Translation Odometry Performance

Dist. (m)	Odometry Response			Actual Position			Error		
	X (m)	Y (m)	φ (deg)	X (m)	Y (m)	φ (deg)	X (m)	Y (m)	φ (deg)
1.0	1.0006	-.00001	-.0005	1.005	-.0045	-.039	.0044	-.0045	-.0385
2.0	2.0006	-.00001	-.0002	2.0075	-.0065	0.039	.0069	-.0065	0.0392
4.0	3.9998	-.00002	0.0	4.01	-.0265	-.271	.0102	-.0265	-.271

Lateral translation—The vehicle was commanded to translate left and stop. The distances and measurements are shown in Table X.

Table X - Lateral Translation Odometry Performance

Dist. (m)	Odometry Response			Actual Position			Error		
	X (m)	Y (m)	φ (deg)	X (m)	Y (m)	φ (deg)	X (m)	Y (m)	φ (deg)
1.0	0.0	1.0006	0.0	.004	0.9775	0.194	.004	-.0231	.194
2.0	0.0	2.0006	0.0	.011	1.9475	0.350	.011	-.0531	.350
4.0	0.0	3.9999	0.0	.021	3.946	-.078	.021	-.0539	-.078

Rotation—The vehicle was commanded to rotate counterclockwise and stop. The distances and measurements are shown in Table XI.

Table XI - Rotation Odometry Performance

Rot (deg)	Odometry Response			Actual Position			Error		
	X (m)	Y (m)	φ (deg)	X (m)	Y (m)	φ (deg)	X (m)	Y (m)	φ (deg)
45	0.0006	.0008	45.13	0.001	.005	44.6	0.0004	0.0042	-0.53
90	0.0021	.0051	90.7	0.0005	.0045	89.26	-.0016	-.0006	-1.44
180	-.0015	.0021	180.3	-.01	.008	178.5	-.0085	0.0059	-1.80

Closed Circuit with Navigation Odometry Updates- The vehicle was commanded around the closed circuit inspection course using 4 landmark update stations. Vehicle position and angular error were measured on the floor before and after landmark updates. The results are shown in table XII.

Table XII - Vehicle Positioning Accuracy

Land Mark Station	Distance Traveled	Angle Traveled	Before Land Mark Update		After Land Mark Update	
			Position Error	Angle Error	Position Error	Angle Error
1	2.68 m	90 deg	.034 m	.93 deg	.015 m	.79 deg
2	4.31 m	0 deg	.0065 m	.27 deg	.01 m	.08 deg
3	1.55 m	180 deg	.022 m	1.54 deg	.013 m	0 deg
4	3.74 m	0 deg	.041 m	.24 deg	.042 m	.08 deg
Average Error			.026 m	.75 deg	.020 m	.24 deg

5.4.4.2 Landmark Sighting

Landmark targets are mounted in known positions in the facility. The landmark sighting subsystem corrects vehicle position periodically (as shown in Table XII) using an iterative algorithm that adjusts vehicle pose to minimize angular errors between predicted and measured directions to landmarks. During Phase I testing the average positional error after navigation update was 2.0 cm, and the average orientation error after update was 0.24 degrees. A discussion of the accuracy of the pose estimation technique can be found in [Sklair91]. The IMSS application of this technique uses targets sized and located so as to fill approximately one half of the camera field of view.

5.4.4.3 Path Planning

The offline generated path planning sequences were successfully used to position the vehicle for the inspection demonstration.

5.4.4.4 Trajectory Generation

Correct trajectory generation was indirectly verified by successfully reaching commanded cartesian locations and by measuring acceleration time and constant vehicle velocity during commanded moves.

5.4.4.5 Obstacle avoidance

Obstacle avoidance was tested by commanding the vehicle to move to a position that would bring it into contact with an obstruction. In all cases when the obstruction was in the ultrasonic sensor field of view the vehicle stopped short of the obstruction.

5.4.5. Sensing Subsystems

5.4.5.1. Laser Ranging

The key performance parameters of any range imaging sensor are listed in Table XIII. We will measure these parameters to characterize our sensor. In addition, Besl [1989] defines a "figure of merit" which combines the most important factors into a single quantity. The figure of merit M is defined as:

$$M = \frac{L_r}{\sigma_r \sqrt{T}}$$

where L_r is the depth of field, σ_r is the RMS range accuracy, and T is the pixel dwell time.

Table XIII - Characteristics of a range imaging sensor (from Besl [1989]).

Parameter	Symbol	Description
Depth of field	L_r	Maximum minus minimum range
Range accuracy	σ_r	Statistical deviation of measurement from true values
Pixel dwell time	T	Effective time to measure depth for a single pixel
Pixel rate	$1/T$	Range pixels per second
Range resolution	N_{bits}	Smallest change in range that sensor can report
Image size	$N_x \times N_y$	Height and width of image
Angular field of view	$\theta_x \times \theta_y$	
Lateral resolution	$\theta_x / N_x \times \theta_y / N_y$	
Standoff distance	L_s	Minimum range
Nominal field of view	$(L_s + L_r/2)\theta_x \times (L_s + L_r/2)\theta_y$	
Frame time	$T \times N_x \times N_y$	
Frame rate	$1/(T \times N_x \times N_y)$	

There are a number of design factors that determine the characteristics in Table XIII. These include: The focal length of the cameras, their spacing with respect to the laser, their orientation with respect to the laser, and laser power. Where possible, we will vary these factors to determine their effect on performance.

The performance criteria and capabilities achieved in Phase I were noted in Table IIb. By adjusting tip threshold a 100% Probability of Detection (POD) rate with 0% false positives was achieved for drums tilted more than 3 degrees. Figure 24 shows drum tip angle measurements from the WSF mockup. Likewise by adjusting the dent depth vs. dent detection threshold a 100% POD with 0% false detections was achieved for dents deeper than 1 inch. Figure 25 shows dent area measurements in the WSF. A range image of a dented drum is shown in Figure 26. Enhanced bulge detection will be incorporated in Phase II by adding ribs to the drum model used in dent detection.

5.4.5.2. Vision

Feature extraction and classification algorithms described in Section 5.1.6.2 were evaluated during parametric testing in the WSF mockup. Combinations of camera-to-drum distance, lens size and iris opening, amount of drum in image, and vehicle operational requirements were also compared. These parameters will be optimized for the specific conditions at the Phase II Demo site. Many images of different drums under nominal conditions were taken in the truckwell for algorithm development. One result is that two video lamps significantly improved rust and corrosion detection in poor ambient light. The lamps also nearly washed out the bar code label on black drums (too much contrast), but locating the bar code labels doesn't require special light so these frames can be digitized without the lamps. Another result is that using the orthogonal feature space (Ohta colors from RGB) makes defect detection easier, so that CPU-intensive classifiers (e.g., k-means) were not needed in Phase I. Algorithms will be optimized and ported for on-board processing in Phase II.

The performance criteria and capabilities achieved in Phase I were noted in Table IIb. Over 500 Mbytes of RGB images were taken during development and testing from the 38 drums in our WSF mockup, from 8 additional drums in our lab and from Government-supplied color photos of drums in DOE WSF's. Since we have a small sample size of defects (e.g., 22 realistic rust spots), the following results were taken from 3 autonomous test runs in the WSF mockup. All rust spots greater than 0.25" (diameter) were positively identified with no false calls. For rust spots greater than 0.1" diam (pea-sized), 91% were correctly identified with a 14% false positive rate. The POD for rust can easily be improved in Phase II by specifying (by examples from trained human inspectors) exactly what constitutes rust that is of concern. Most of the rust spots missed were faint rust caused by scratched paint and outdoor exposure. False positives were caused by rust spots on floor, markings on walls above top row of drums, red paint chips, and plywood separators. Most of these factors can be filtered out in Phase II. For rust streaks with width greater than 0.1" the detection rate was 92% with a 10% false positive rate. The algorithm (based on color thresholding and shape filtering) does distinguish between salt-water streaks and true rust streaks, while ignoring faint streaks. For corrosion (bubbled paint spots greater than 0.1" diam) a 92% detection rate was achieved, with 5% false calls. Note that only 1 drum had true corrosion spots (12). The corrosion algorithm uses color thresholding and texture classifiers with a connected component analysis that combines nearest neighbors.

Several figures follow illustrating image processing results from autonomous inspection test runs in the WSF mockup. Detected defects are automatically high-lighted for quantification (for reports and defect data base) Figure 27 shows a white drum in the poorly lit truckwell (WSF). The goal is to identify regions of bubbled paint due to a corrosive agent (corroded paint does not show well in this hardcopy). Results are shown in Figure 28 (missing paint at bottom is found by a separate process). For a white test drum, Figure 29 shows the three input frames from the color camera. Figure 30 then shows 2 sample frames of rust detection (on left) and 2 sample frames of streak detection (on right). For a black test drum, Figure 31 shows the three input frames from the color camera (the visible streaks here are due to the salt-water spray applied to induce rust - the streak analysis has to distinguish between residue salt streaks and streaks containing true rust). Figure 32 then shows 2 sample frames of rust detection on the left and streak detection on the right (no rust or streaks occurred in the other frames). Note that rust spots (large and small) were successfully identified (with no false calls) even when the top frame includes the bright yellow-and-red Hazardous Waste label. The identified streak regions also contain small amounts of rust.

Figure 24 - Tip Angle Measurements

Figure 25 - Dent Area Measurements

Figure 26 - Range Image of Dented Drum

Figure 27- Original Image of Barrel with Corrosion in Center

Figure 28 - Processed Image of Barrel with Corrosion in Center

Figure 29 - Three Input Frames of White Drum

Figure 30 - Processed Frames of White Drum (rust on left, streaks on right)

Figure 31 - Three Input Frames of Black Drum

Figure 32 - Processed Frames of Black Drum (rust on left, streaks on right)

5.4.5.3 Bar Code Scanner

Parametric testing determined maximum scanner distance from drum for efficient operation (minimum is 5cm). From numerous measurements a conservative max distance is 30cm, at angles up to 25 degrees. If the label is straight-ahead, the scanner can read it at up to 50cm. The laser timeout period (now set at 1 second) will also be varied to try and improve decoding at larger distances and angles. The scanner always returns the correct ASCII code, or the no-decode symbol - no partial reads are possible. The goal during testing is to minimize vehicle repositioning for scanning. Although the special wheels make repositioning easy, it does consume time and power. The Phase II scanner will read labels at larger distances and angles.

5.4.6. Executive

There are three major performance criteria for the mission executive. First, the system must perform a complete inspection of the site, ensuring that all faults detectable following EPA guidelines can in fact be detected, by following the generated inspection sequence. Second, the system must perform efficiently, as measured by time to inspect, and the cost to the system (e.g. battery usage, wear on vehicle parts). Third, the system must be robust in the face of the anomalies that may occur within the inspection sites.

For this phase of the contract, complete inspection is guaranteed by maintaining a check that all views accessible on each barrel are recorded for both the stereo and color vision modules, and that each bar code that is visible is read. This can be verified by reading the data returned at the end of the inspection procedure, and comparing it with either the test/demonstration set-up, or the simulated data used for the test. Branches of the inspection procedures, for both unfaulted and faulted drum detection were tested in the demonstration/ test site.

One of the potential errors that can occur with a highly efficient inspection procedure is the storage of data with the wrong drum id. This is because the actions of finding an individual drum, identifying its bar code, and inspecting various sections of the drum can occur far apart in the inspection sequence⁶. Proper storage of inspection data was verified in the demonstration/test area. This included a mix of drum faults, and multiple faults on individual drums.

The efficiency of the inspection process is a function of the amount of time it takes to inspect a site, the cost of vehicle resources, such as power, and the costs associated with degradation of the vehicle and sensor equipment with usage, such as gimble or motor life. Because the vehicle currently being used is not the target delivery vehicle, we are not measuring vehicle-specific parameters in this phase. In the subsequent phase sensors will be placed on the vehicle to measure resource usage for each of the operations, and estimates will be made for any significant effect of equipment usage on the life span of the equipment. In this phase, the measure used to evaluate inspection procedure efficiency is the overall time for execution of the procedure. This is probably the most important factor in the efficiency of the procedure, and is highly correlated with the other measures (power usage, etc.). The mission executive will not be optimizing the inspection procedure by the end of this phase. Optimization strategies will be completed in phase two. However, measures comparing the time to run following various inspection procedures will be performed in order to provide guidelines for subsequent work in optimization.

The reliability of the IMSS in operations will be partly determined by the ability of the vehicle to perform appropriately in a range of anomalous situations. Although these anomalies should be rare, the target environment consists of a huge number of drums. To achieve reliability across many months of operation, even rare occurrences should not degrade the performance of the IMSS. The site environment is both stable and benign to the vehicle. Thus, it is predicted that only a small range of anomalies will be observed, and these will be accommodated. Anomalies such as barrel out of place, missing, or missing bar code label are expected, and can be handled with fairly simple heuristic plan repair strategies. Small obstacles are easy enough to avoid, given the soft bumpers and simple heuristics for navigating around objects. Large obstacles can also be accommodated by inspecting the aisle from each end of the aisle, and going down the aisle as far

⁶ The most efficient inspection could entail e.g., proceeding down an aisle, and stopping every so many feet to identify the next drums on the left and right, inspect the nearest faces, going to the end of the aisle and coming back, inspecting the other face of each drum, without checking the bar codes. In this case great care must be taken to ensure that in returning down the aisle, the right data is stored with the correct drum id.

as the obstacles. Anomalies that are more complex than these are both highly unlikely, and should probably be reported immediately back at home base. Where the vehicle finds itself unable to recover the inspection process given the simple heuristics described above, it will return to home base, and report whatever data were collected regarding the problem.⁷ Unfortunately, because of limitations of the ultrasonic collision avoidance system most of the tests of realtime replanning were not feasible. Table XIV shows the performance tests planned for the Executive for phase 1.

Table XIV - Phase One Executive Performance Tests

	Demonstration Facility Test
Plan Generation	- Complete inspection route generated
Plan Dispatching and Monitoring	- Plan followed - All module actions coordinated correctly - All data stored correctly - All conditional branches verified. - Multiple drum faults tested - Inspection time measured
Replanning	- Multiple faults tested.

5.4.7. Operator Interface

5.4.7.1. Vehicle Operation

Although no parametric testing was done, all components of the Vehicle Operation menus were functionally tested and performed successfully. The operator-in-the-loop capability provided by this interface was found to be extremely useful during testing and integration of the subsystem components.

5.4.7.2. Task Assignment

All components of the Task Assignment interface were functionally tested and were successfully used to initiate and monitor the progress of inspection missions.

5.4.7.3. Reporting Data Base

The database implementation includes search tables for rapidly accessing drum and landmark records via the barcoded identifier. These tables are sorted lexically by the label identifier string after the database is loaded from a disk file. These tables are searched for the appropriate identifier when a command requests data by label. Using a binary search, at most 10 table entries need to be checked for a 1023-entry database.

The basic record types required the following amounts of data storage in bytes: Drum – 60; DrumType – 36; Obstacle – 20; and Landmark – 48. The containing-type records storage requirements depend on the number of contained elements, such as drums per aisle. For the small demonstration facility model (12 drums total, 12 drums per area, 8 drums per aisle, 8 aisles total, 8 aisles per area, 2 areas), the containing-type records required the following amounts of data storage in bytes: Aisle – 44 and Area – 96; and the overall facility model required 2,124 bytes (2.1 kb) of storage. For the large facility model (2000 drums total, 1000 drums per area, 100 drums per aisle, 20 aisles total, 10 aisles per area, 2 areas), the containing-type records required the following amounts of data storage in bytes: Aisle – 228 and Area – 2076; and the overall facility model required 129,572 bytes (126.5 kb) of storage.

⁷ Given the well-controlled environments at these sites, it is more likely that if the vehicle fails here that there is a vehicle problem that manifests itself as a problem in the environment. For instance, if the vehicle repeatedly reports that barrels are missing, a sensor may need to be repaired. Return to home in this case is desirable, since the data collected will be faulty anyway.

5.4.8. Safety Systems

The safing system was functionally tested. Functional testing included command rejection while safed and aborting an executing move both manually and through software. No parametric testing was performed.

6. RESULTS AND DISCUSSION

6.1. Mechanical Subsystems

6.1.1. Motion Platform

Results - The mechanical elements of the vehicle motion control system proved more than satisfactory for the phase one demonstration scenario.

Discussion - The substantial changes required for a phase 2 prototype vehicle demand reconsideration of the wheels and steering system used.

6.1.2. Sensor Platform

Results - The mechanical elements of the scan platform motion control system proved more than satisfactory for the phase one demonstration scenario.

Discussion - The system used for the phase one vehicle is inadequate for the phase two prototype. The phase one configuration did not allow bar code reading of second-tier barrels nor inspections of barrels higher than the second tier. Considerations for phase two include a mast with multiple sensor suites, an articulated mast with fewer sensor suites, or a dexterous manipulator. An analysis will be required to select the best topology.

6.2. Electrical Subsystems

6.2.1. Vehicle Electronics

Results - The control electronics have performed adequately.

Discussion - The control electronics on the existing vehicle were not originally designed to minimize space requirements and maximize power efficiencies, nor were they designed specifically for the barrel inspection task. There is a significant amount of electrical equipment on board that is not necessary for this contract. For phase two, analyses will be required to select the best topologies and devices.

6.2.2. Ultrasonic Transducers

Results - The ultrasonic sensors do not provide adequate coverage to successfully implement a usable collision avoidance system. However, the system did show proof of concept and was adequate to provide a test environment for the collision avoidance kinematics.

Discussion - The existing ranging system is inadequate for the phase two vehicle. Additional sensors with an increased detection angle will be probably be required. The precise configuration of the phase two collision avoidance system will not be known until the vehicle form factor is known.

6.2.3. Communications

For phase two, there will be no tether providing communications or power. Medium-rate data communications will be available via a radio modem link when the vehicle is within range of its recharging station or the operator console. All video information will be processed on-board.

The communications interfaces developed for phase one, can be reused since the embedded operating system, VRTX, supports socket communications between tasks on a single processor, as well as between processors on the same backplane.

6.2.4. Power

Results. - The power system has performed adequately under all load conditions.

Discussion - The battery power system on the existing vehicle was not designed for extended untethered vehicle operation, nor were the electrical systems designed for maximum power efficiency. For instance, VME systems typically have higher power requirements than some other commercially available bus topologies such as STD32 bus. For phase two, an analysis will be necessary to maximize vehicle power efficiency and the size vs. capacity trade-off for the power delivery system. Some additional monitoring systems will be added to ensure that the vehicle always has enough reserve power to reach a recharging station.

6.3 Control

6.3.1 Vehicle

The onboard vehicle position control implementation has functioned satisfactorily in all testing. PD wheel position control compensation has been all that is required to provide adequate velocity tracking performance. Good tracking accuracy is indicated by agreement of commanded position and position derived by odometry. This is shown in Table XII. Vehicle velocity and acceleration limits of .4 m/s and 2 m/s^2 respectively have been used for the majority of testing and found to be adequate.

Errors between actual position and odometry are also shown in Table XII. The largest errors occur in rotation and vehicle y-position. These errors probably result from wheel to wheel rolling radius variations and misalignments of wheel axles and running surface nonuniformity.

6.3.2 Obstacle Avoidance

The onboard collision avoidance system was implemented for two modes of operation. The first mode can provide vehicle motion corrections in all three vehicle degrees of freedom (x, y, phi). In this mode virtual forces at ultrasonic sensors also produce virtual torques about the vehicle center to cause vehicle rotation. This mode is probably most useful for contouring around large obstacles. The second mode provides vehicle motion corrections in x and y only. Virtual torques are ignored, so no rotations are possible. This mode will be useful for keeping the vehicle centered in long narrow aisles where navigation position corrections using landmark updates may not be possible. Due to the narrow beam (10 deg) and small number (8) of ultrasonic sensors employed, gaps in coverage at the sides, front and back of the vehicle were observed. This will be corrected in the phase 2 design by using wide field of view sensors and more sensors to provide complete coverage.

Impedance Filter

A mechanical damper model ($1/b$) was used for the impedance filter. Using this simple model results in vehicle velocity commands proportional to the obstacle avoidance virtual force. This causes the vehicle to move at a constant velocity away from an obstacle producing a constant virtual force on the vehicle. Transients are smoothed using wheel acceleration limits available in the Galil motion control boards.

Virtual Force Filter

A virtual force proportional to the reciprocal of distance to the obstacle was used instead of the proposed inverse square law characteristic. This form was found to be well behaved even when the vehicle was constrained on opposite sides.

6.3.3 Scan Platform

Precise control of pan and tilt proved to be somewhat difficult due to the presence of a large amount of mechanical backlash in the gearheads employed. As much as .5 deg of backlash was observed at the pan and tilt axis. Sensing of pan and tilt angles is outboard of the backlash so pointing knowledge is not affected. However, control limit cycling and instability prevented use of the integral term in control compensation. A PD controller with low bandwidth (1 Hz) resulted in a stable loop with reduced tracking and pointing accuracy. It was also necessary to counter balance the tilt axis with approximately 10 lbs of weight to minimize backlash effects.

6.4. Navigation

The approach of the IMSS navigation system is to use data from sensors already on the vehicle (wheel position and video camera) in combination to provide real-time vehicle pose data with occasional landmark updates. This approach required no modifications to the vehicle systems, and only passive target additions to the facility site. Other approaches are possible, for example a radio frequency range and bearing type system. Such an approach is independent of other vehicle systems, but requires additional facility infrastructure (antennas, transmitters).

6.4.1 Wheel Odometry

The performance of the wheel odometry was affected by the floor surface characteristics wheel rolling radius variations and wheel misalignment. A slippery floor, such as linoleum tile, was observed to increase the position estimation error. This can be compensated by more frequent landmark sightings.

6.4.2 Landmark Sighting

It should be noted that the pattern of target features (the concentric circles) can be varied, as long as the model is defined for the vision system. A large landmark target with a model distinct from the wall and column-mounted targets may be mounted on the facility ceiling if it is high enough. This will provide a global position estimation capability. Although the accuracy will probably not be sufficient for regular use, it would serve to locate the vehicle within a specific aisle, followed by a subsequent movement to and sighting of a known landmark target. This allows the vehicle to perform a rapid autonomous self-localization within the facility.

6.4.3. Path Planning

In the phase 2 design path planning and obstacle avoidance will have to work together to handle response to path blocking obstacles, for example, detecting a blockage in an aisle and replanning a path to exit the aisle and continue the inspection. Also, in long aisles where landmark updates to navigation are not practical, the path planner could utilize obstacle avoidance to maintain vehicle centering in the aisle and control only longitudinal motion.

6.4.4. Trajectory Generation

The present method of moving the vehicle from position to position using acceleration and velocity limited trajectories has performed very well and therefore will also be used in phase 2.

6.4.5. Obstacle avoidance (see discussion in 6.4.3)

6.5. Sensing Subsystems

6.5.1. Laser Ranging

Performance results were described in Section 5.4.5.1. The structured light system performed very well, and further characterization of dents, bulges and tipped drums for the Phase II Demo site will help improve the algorithms. One area of potential improvement in the laser range imaging system is to use multiple light stripes instead of a single stripe. This would dramatically reduce the scanning time since instead of having to sweep a single stripe through an angle of $\Delta\phi$, it would only be necessary to sweep N stripes simultaneously through $\Delta\phi/N$. Lasiris, Inc makes a laser line projector with up to 19 parallel lines. This would be a simple low cost improvement that would speed up data collection.

Another area of potential improvement in accuracy would be to use a dedicated custom sensor for the light stripe imaging instead of generic CCD cameras. This would allow higher resolution elements to be used, and avoid the limitations of the NTSC analog signal bandwidth. Another improvement with a custom sensor is to tilt the detector plane with respect to the lens so that any points on the light ray are perfectly in focus (this is known as the Scheimpflug configuration). The cost of these improvements would have to be balanced against the increased accuracy provided.

6.5.2. Vision

Performance results were described in Section 5.4.5.2. Overall the color vision system performed well at correctly identifying rust, streaks and corrosion. Image analysis performance and accuracy will be improved by tuning the system for specific site requirements. For example, knowing expected drum condition (new/old, clean/dirty), drum color, and size and strength of rust, streaks and corrosion (small/large; heavy/light) influences several models and threshold parameters in the algorithms. Smaller camera bodies with more sensitive CCD chips could also help visual anomaly detection under variable lighting conditions.

6.5.3. Bar Code Scanner

The scanner used for the phase 1 demonstration has a maximum range of approximately 16 inches. This range limitation prevented reading of bar codes of level 2 barrels. Level 1 barrel codes were read reliably at a nominal distance of about 13 inches at a fixed height from the floor. The phase 2 implementation will allow pointing of the bar code reader laser in pan and tilt to locate out of place bar codes on barrels. Low power, low cost lasers that scan labels at distances greater than 1.0m are commercially available and will be evaluated in phase two.

6.6. Executive

6.6.1. INSPECTION COMPLETENESS

Plan Generation - The plan generation algorithm described in section 5.1.7 above successfully generates a complete inspection sequence given inputs about drum locations.

Plan Dispatcher/Monitor. This module contains all necessary interfaces to each of the controlled modules: vehicle, scan platform, stereo-vision, color vision and bar code reader. Each of the control interfaces are fully specified. The system successfully coordinated all motion and sensing to acquire a complete inspection of the site. The coordinated motion demonstrated included a high degree of overlapping actions that increase the efficiency of the inspection process.

6.6.2. INSPECTION EFFICIENCY

In phase 1 measures of efficiency are entirely based on inspection sequence time. In phase 2, energy (battery) usage will be an additional measure used in evaluating efficiency. Time to inspect and energy usage are highly correlated - both are primarily related to the amount of motion of the vehicle and the scan platform. Therefore, it is expected that most of the strategies that achieve efficiency when only time is considered will also lead to efficient energy usage. There may be some variations, however, especially since scan motions can be slow relative to vehicle movement, but energy usage is higher for vehicle movement than for scan platform movement. Thus, any trade-offs that can be made by increasing scan motions to decrease vehicle motions, or vice-versa, may have different outcomes.

Overall, the system averaged a little less than a minute a drum for inspection time for the 40 drum facility. The speed with which this was accomplished was due to the efficiency of the plan in reducing state changes, most notably in the scan platform position, and providing for concurrent performance of inspection tasks.

Plan Generator. Average inspection time per drum following the algorithm described in 5.1.7.2 above can be compared to inspection time per drum given other algorithms. We will ignore the clearly inefficient algorithms, such as random selection of next drum to inspect, or next inspection position. The best contrasts are 1) sequences in which the order of operations within inspection of a single drum are not ordered with respect to the various positions the scan platform must attain, and 2) where the sequences of operations for the inspection of a single drum are not ordered to maximize concurrency. Using the average expected times under these two conditions, the comparison results are as follows. The algorithm used for plan generation as outlined in 5.1.7.2 averages 57 seconds/drum. Contrast 1 (ordering without minimizing scan movements) averages 65 seconds/drum (114% of the algorithm used), and contrast 2 (ordering without maximizing concurrency) averages 84 seconds/drum (147% of the algorithm used).

Plan Dispatcher/Monitor. The algorithm described for plan monitoring allows for concurrent performance of various inspection operations. The contrast is a system which only performs inspection operations one at a time. The current system performs averages 57 seconds/drum. A strictly sequential inspection sequence would average 111 seconds/drum (195% of the concurrent performance algorithm).

Speed of inspection for the current vehicle and sensor configuration is limited by the length of time needed to complete the structured light (dent and tilt) inspection task. The processing time for this operation is 47

seconds/drum. Since there is only one processor for this operation, this is the lower limit for drum inspection time with the current configuration. Changes in the hardware configuration and optimization of the image processing code will probably reduce this limit in phase 2, so faster inspection time may be achieved.

The plan monitor and dispatcher was designed to monitor the progress of each module and its required states and control. Because of this, changes in the hardware and software that will allow speeding up the overall inspection sequence will easily be accommodated by the Executive.

6.6.3. Performance in Anomalous Situations

Real Time Replanner. Rudimentary reactive capabilities were implemented but were for the most part untestable, due to ultrasonic sensor limitations. Sensor anomalies which would not interrupt the inspection sequence were tested successfully.

6.7. Operator Interface

6.7.1. Vehicle Operation

The low-level vehicle and scan platform control functions provided by the operator interface will still be present in the phase two system. There is no additional hardware or software requirement to keep them, although a smaller joystick will be used for manual teleoperation. The man-in-the-loop capability of this interface will be useful during initial set-up of the system, and for occasional operations such as moving the vehicle to a maintenance area.

6.7.2. Task Assignment

The facility layout screen will have to be modified for storage facilities containing more drums than can be represented using the current circular button size (approximately 50 drums at floor level). A medium-size facility can be handled by simply using smaller buttons, up to approximately 300 drums at floor level. Beyond that, the scale is too small for accurate touch screen operation. To allow touch screen operation for a large facility, scrolling between areas can be achieved within the existing interface framework, by using buttons at the edges of the screen. One could still view the entire facility map on a single screen for monitoring vehicle progress; however, the individual drums would be too small for selection on this screen.

6.7.3. Reporting Data Base

The database can be readily implemented as part of an embedded software package on-board the vehicle for phase two, since it uses the standard interface library. The facility model and reporting database commands are already implemented as individual procedures.

6.8 Safety Systems

Results - The safety system has performed adequately under all conditions.

Discussion - The Phase I safety system was comprised mainly of a manually operated kill switch. This approach is obviously inappropriate for the Phase II prototype. Safety systems for the Phase II vehicle may include an ultrasonic collision avoidance system, mechanical 'soft' bumpers, current monitors for the motor amplifiers, battery voltage and current monitors, and other vehicle health monitors. The soft bumpers will disable the motor amplifiers if the vehicle comes into contact with an object. This action will not depend on software. The motor amplifiers will also be disabled if an over-current condition is detected.

7. CONCLUSIONS

A prototype barrel monitoring and inspection system was successfully demonstrated in a high fidelity waste storage facility mockup. 92% (worst case) of all anomalies were successfully detected with only 14% (worst case) false positive detections.

The IMSS system that was developed included new or upgraded autonomous navigation and obstacle avoidance systems, advanced visual and laser based inspection sensors and analysis software, and automatic task assignment and report generation software in the multilevel operator console. A complete safety system was installed with rigorous handshaking command-response sequences and with several automatic safing procedures.

This program is now ready to proceed to the next phase to build a commercial prototype that meets the physical constraints of an actual waste storage facility and to demonstrate the prototype onsite for evaluation by a Waste Operations Group. Calculated costs based on prototype system performance and current facility operation costs indicate a 4:1 cost savings. Several DOE facilities (Hanford, Oak Ridge National Laboratory, and Los Alamos National Laboratory) have expressed an interest in obtaining such a system. Completion of phase two within the fifteen month timeframe will prove this technology in time to support the many new waste storage facilities being brought online to support the ER&WM process.

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LIST OF ACRONYMS AND ABBREVIATIONS

A	Amperes
ALARA	As Low As Reasonably Achievable
ASCII	American Standard Character Information Interchange
ATP	Authority To Proceed
AWG	American Wire Gauge
CAD	Computer Aided Design
CAM	Computerized Air Monitor
CCD	Charge Couple Device
CDR	Critical Design Review
CFR	Code of Federal Regulations
cm	centimeters
DC	Direct Current
DOE	Department Of Energy
EPA	Environmental Protection Agency
ER&WM	Environmental Remediation and Waste Management
GPS	Global Position System
H/W	HardWare
IMSS	Intelligent Mobile Sensing System
IR	Inductive and Resistive
I/O	Input / Output
MHz	MegaHertz
MMAAG	Martin Marietta Astronautics Group
mW	milliWatt
nm	nanometer
NTSC	National Television Standard Connector
PID	Proportional Integral Derivative
PRDA	Program Research and Development Agreement
PROM	Programmable Read Only Memory
PWM	Pulse Width Modulated
RAM	Radiation Air Monitor
RAM	Random Access Memory
RGB	Red Green Blue
R&D	Research and Development
S/W	SoftWare
TBD	To Be Determined
TCP/IP	Transmission Control Protocol / Internet Protocol
V	Volts
WSF	Waste Storage Facility
3D	Three Dimensional

Appendix A – Database Commands and Data Structures

Table A-I Facility Model Query Commands

Command	Argument	Response
SEND_FACILITY_INFO	(none)	FacilityInfo
SEND_AREA_INFO_BY_INDEX	Index	Area
SEND AISLE_INFO_BY_INDEX	Index	Aisle
SEND_DRUMTYPE_INFO_BY_INDEX	Index	DrumType
SEND_DRUM_INFO_BY_INDEX	Index	Drum
SEND_DRUM_INFO_BY_IDENT	Ident	Drum
SEND_DRUM_INFO_BY_LOC	Loc	Drum
SEND_LANDMARK_INFO_BY_INDEX	Index	Landmark
SEND_LANDMARK_INFO_BY_IDENT	Ident	Landmark
SEND_LANDMARK_INFO_BY_LOC	Loc	Landmark
SEND_OBSTACLE_INFO_BY_INDEX	Index	Obstacle
SEND_OBSTACLE_INFO_BY_LOC	Loc	Obstacle

Table A-II Defect Database Report Commands

Command	Argument	Response
REPORT_PATCH_BY_INDEX	PatchIndex	(none)
REPORT_STREAK_BY_INDEX	StreakIndex	(none)
REPORT_DENT_BY_INDEX	DentIndex	(none)
REPORT_TIPPED_BY_INDEX	TippedIndex	(none)
REPORT_BULGE_BY_INDEX	BulgeIndex	(none)
REPORT_NODRUM_BY_INDEX	NodrumIndex	(none)
REPORT_LOCDRUM_BY_INDEX	LocdrumIndex	(none)
REPORT_NOLABEL_BY_INDEX	NolabelIndex	(none)
REPORT_LOCLABEL_BY_INDEX	LoclabelIndex	(none)
REPORT_BADLABEL_BY_INDEX	BadlabelIndex	(none)

Table A-III Facility Model Update Commands

Command	Argument	Response
UPDATE_DRUM_LOC_BY_IDENT	LocIdent	(none)
UPDATE_DRUM_LOC_BY_INDEX	LocIndex	(none)
ADD_NEW_DRUM_TO_LIST	Drum	(none)

Table A-IV Facility Model DrumType Data Record Structure

Element	Description
radius	Half diameter of drum body [m]
height	Base to top of rim [m]
lid_radius	Half diameter of lid ring [m]
rib_radius	Half diameter of rib [m]
base_radius	Half diameter of base ring [m]
rib_height[MAX_NUM_RIB_DRUM]	Base to center of each rib [m]
rib_count	Number of ribs (usually 2 or 3)

Table A-V Facility Model Drum Data Record Structure

Element	Description
x_location	Drum X coordinate in facility frame [m]
y_location	Drum Y coordinate in facility frame [m]
z_location	Drum Z coordinate in facility frame [m]
orientation	Drum orientation (yaw) in facility frame [rad]
label_height	Height of label center above base [m]
drum_type	Code for drum type:
color	Code for basic color:
stack_level	Height within stack (bottom = 1)
in_area	Area containing drum
on_aisle	Primary aisle segment containing drum
also_on_aisle	Secondary (crossing) aisle segment containing drum
next_x_pos_ix	Index within drum list of +X neighbor
next_x_neg_ix	Index within drum list of -X neighbor
next_y_pos_ix	Index within drum list of +Y neighbor
next_y_neg_ix	Index within drum list of -Y neighbor
next_z_pos_ix	Index within drum list of +Z neighbor
next_z_neg_ix	Index within drum list of -Z neighbor
index	Index of this drum
identifier[DRUM LABEL LEN+1]	As encoded on barcode label

Table A-VI Facility Model Landmark Data Record Structure

Element	Description
x_location	Landmark X coordinate in facility frame [m]
y_location	Landmark Y coordinate in facility frame [m]
z_location	Landmark Z coordinate in facility frame [m]
axis_x	Landmark X axis of rotation in facility frame
axis_y	Landmark Y axis of rotation in facility frame
axis_z	Landmark Z axis of rotation in facility frame
angle	Landmark rotation about above axis [rad]
in_area	Area containing landmark
on_aisle	Primary aisle segment containing landmark
also_on_aisle	Secondary (crossing) aisle segment containing landmark
identifier[LANDMARK LABEL LEN+1]	As encoded on barcode label

Table A-VII Facility Model Obstacle Data Record Structure

Element	Description
x_corner_1	Obstacle corner 1 X coordinate in facility frame [m]
y_corner_1	Obstacle corner 1 Y coordinate in facility frame [m]
x_corner_2	Obstacle corner 2 X coordinate in facility frame [m]
y_corner_2	Obstacle corner 2 Y coordinate in facility frame [m]
in_area	Area containing obstacle

Table A-VIII Facility Model Aisle Data Record Structure

Element	Description
x_end_1	Aisle end 1 X coordinate in facility frame [m]
y_end_1	Aisle end 1 Y coordinate in facility frame [m]
x_end_2	Aisle end 2 X coordinate in facility frame [m]
y_end_2	Aisle end 2 Y coordinate in facility frame [m]
drum_count	Number of drums along this aisle
drum_ix_list[MAX_NUM_DRUM_AISLE]	Array of indices of drums along this aisle
landmark_count	Number of landmarks along this aisle
landmark_ix_list[MAX_NUM_LANDMARK_AISLE]	Array of indices of landmarks along this aisle

Table A-IX Facility Model Area Data Record Structure

Element	Description
x_corner_1	Area corner 1 X coordinate in facility frame [m]
y_corner_1	Area corner 1 Y coordinate in facility frame [m]
x_corner_2	Area corner 2 X coordinate in facility frame [m]
y_corner_2	Area corner 2 Y coordinate in facility frame [m]
aisle_count	Number of aisles in this area
aisle_ix_list[MAX_NUM_AISLE_AREA]	Array of indices of aisles in this area
drum_count	Number of drums in this area
drum_ix_list[MAX_NUM_DRUM_AREA]	Array of indices of drums in this area
landmark_count	Number of landmarks in this area
landmark_ix_list[MAX_NUM_LANDMARK]	Array of indices of landmarks in this area
obstacle_count	Number of obstacles in this area
obstacle_ix_list[MAX_NUM_OBSTACLE]	Array of indices of obstacles in this area

Table A-X Facility Model Area FacilityInfo Record Structure

Element	Description
area_count	Number of areas in facility
aisle_count	Number of aisles in facility
drum_count	Number of drums in facility
drum_type_count	Number of drum types in facility
landmark_count	Number of landmarks in facility
obstacle_count	Number of obstacles in facility
x_corner_1	Facility corner 1 X coordinate [m]
y_corner_1	Facility corner 1 Y coordinate [m]
x_corner_2	Facility corner 2 X coordinate [m]
y_corner_2	Facility corner 2 Y coordinate [m]
x_home	Home X coordinate in facility frame [m]
y_home	Home Y coordinate in facility frame [m]
yaw_home	Home orientation (yaw) in facility frame [rad]
home_aisle	Primary aisle segment containing home
home_aisle_2	Secondary (crossing) aisle segment containing home
facility_name[FACILITY_NAME_LEN+1]	String identifying facility

Appendix B – Operator Interface Screen Prints

Vehicle Control Screen

Scan Platform Control Screen

Facility Layout Screen

Vehicle Control Screen

Scan Platform Control Screen

Facility Layout Screen

DATE

FILMED

5/19/94

END