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Intelligent Mobile Sensor System for Drum Inspection and Monitoring - Volume I

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Abstract

The objective of the Intelligent Mobile Sensor System (IMSS) project is 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 the narrow free aisle space between rows of stacked drums. The system has an integrated sensor suite for problem-drum detection, and is linked to 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 portions 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 96% of 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 two is now complete. The first phase 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 ARPA contracts and internal research. The second phase demonstrated 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.

This report summarizes the design and evaluation of the new IMSS Phase 2 system and vehicle. Several parts of the IMSS Phase 1 Topical (Final) Report, which describes the requirements, design guidelines, and detailed design of the Phase 1 IMSS vehicle, are incorporated here, with modifications to reflect the changes in the design and the new elements added during the Phase 2 work. The new vehicle design can only be meaningfully described in the context of the foundational Phase 1 design material. Thus, this report serves as a repository for all requirements and design materials for the IMSS Phase 2 vehicle. Phase 2 evaluation and performance results are also reported here.

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1. EXECUTIVE SUMMARY

1.1 Programmatics

This project developed a prototype mobile robot to autonomously monitor and inspect stored waste containers. The problem solved is the weekly inspection of large numbers of drums containing unspecified hazardous, radioactive, and mixed wastes. These drums are stored in large warehouse-like facilities, the drums are palletized (typically four 55 gallon drums per pallet), arranged in rows separated by narrow aisles (36 inches down to 26 inches), and are typically stacked two to five pallets high. Current federal regulations require that all drums be inspected once per week. Reports must positively identify each drum inspected and must generate a separate report for those drums not meeting the inspection limits. Drums 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 Intelligent Mobile Sensor System (IMSS) project consists of three phases, ultimately resulting in a mobile robot system capable of autonomously inspecting and monitoring drums containing stored waste:
- Phase 1 of the project was a technology demonstration and resulted in the development of an engineering model using available hardware to demonstrate and parameterize the mobile robot, its sensing systems, and the mission scenario. Phase 1 had a period of performance of 8 months.
- Phase 2, discussed in this report, developed an operational prototype of the vehicle and its subsystems with additional performance characterization in a high-fidelity mock storage facility. Phase 2 had a period of performance of 18 months.
- Phase 3 will culminate in extended field testing and demonstration to prove commercial viability and robustness.

Figure 1-1 shows the timeline in months for the project, with the milestones defined relative to the start of each phase (ATP). Table 1-1 defines the milestones for the three phases of the project.

Phase 1. There were five main elements of the Phase 1 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.

Phase 2. The engineering effort of Phase 2 focused on four main elements:
- Design and construct a field deployable vehicle (mobility platform and sensor mast);
- Design and evaluate improvements of the mission sensor subsystems;
- Develop a full-scale operator's control station interface; and
- Performance characterization of the integrated system through end-to-end testing in a realistic mock storage facility.

The Future. Phase 3 will focus on improving the mission sensing capability and will culminate with extended field trials at a DOE waste storage facility. 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.
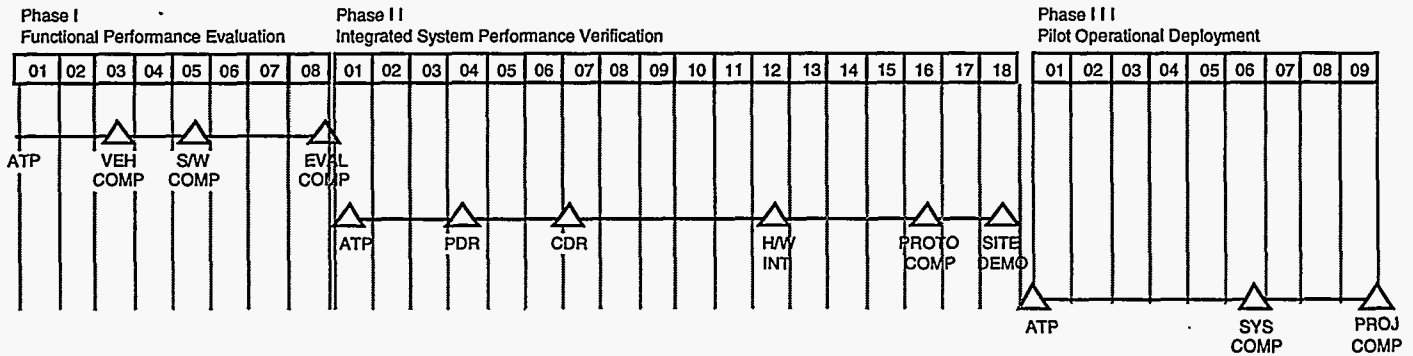
Figure 1-1. Three-Phase Milestone Schedule for Intelligent Mobile Sensor System Project.

Table 1-1. Milestone Definition Log.

Phase	Milestone	Definition
1	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.
2	Preliminary Design Review	Specifications have been reviewed; the preliminary design is complete and has been compared against the specifications and with each other for compatibility
	Critical Design Review	Detailed engineering design for field deployable system is complete. Review of design has occurred with no significant discrepancies. Ready to manufacture.
	Hardware Integrated	The hardware and components have been assembled into a physically complete unit ready for the addition of software.
	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.
3	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, evaluated, and certified at an operational site.

1.2 The Vehicle

The IMSS Phase 2 vehicle, a true operational prototype vehicle, designed and manufactured during Phase 2, is shown in Figure 1-2. The new vehicle features a number of improvements based on experience during Phase 1 with the IMSS Phase 1 vehicle, including:

- Mobility platform measuring 21 in. wide by 39 in. long, allowing navigation through narrower aisles. (Phase 1 vehicle dimensions precluded navigation through the required aisle-widths.)
- Articulated sensor mast hosting three sensor suites, allowing simultaneous viewing of a three-high stack of drums. Modular design allows integration of a fourth top-level sensor suite. (Phase 1 vehicle has a sensor mast only capable of inspecting drums stacked two high.)
- Self-contained battery power system providing 4 kW-hours at 48 volts, with 10-12 hours of operation at room temperature on a single charge. (Phase 1 vehicle depends on tethers for power and communication with the off-vehicle computers.)
- All mission executive planning and scheduling, and DSP-based image analysis done on-board in real-time. (Phase 1 vehicle does this off-vehicle via a network of UNIX workstations.)
- Data storage of defect logs, databases, and drum images to an on-vehicle hard disk drive.
- Feature-based navigation using only pre-existing facility landmarks such as pallets and drums. (Phase 1 vehicle requires use of special landmark target sightings for navigation, which requires modifications to a facility.)
- Hardware and software safety systems, including skin-mounted contact sensors, ultrasonic transducers for collision detection and avoidance, battery parameter monitoring, etc.
- Automated recovery from operational anomalies such as obstacles, blocked aisles, and equipment failures.
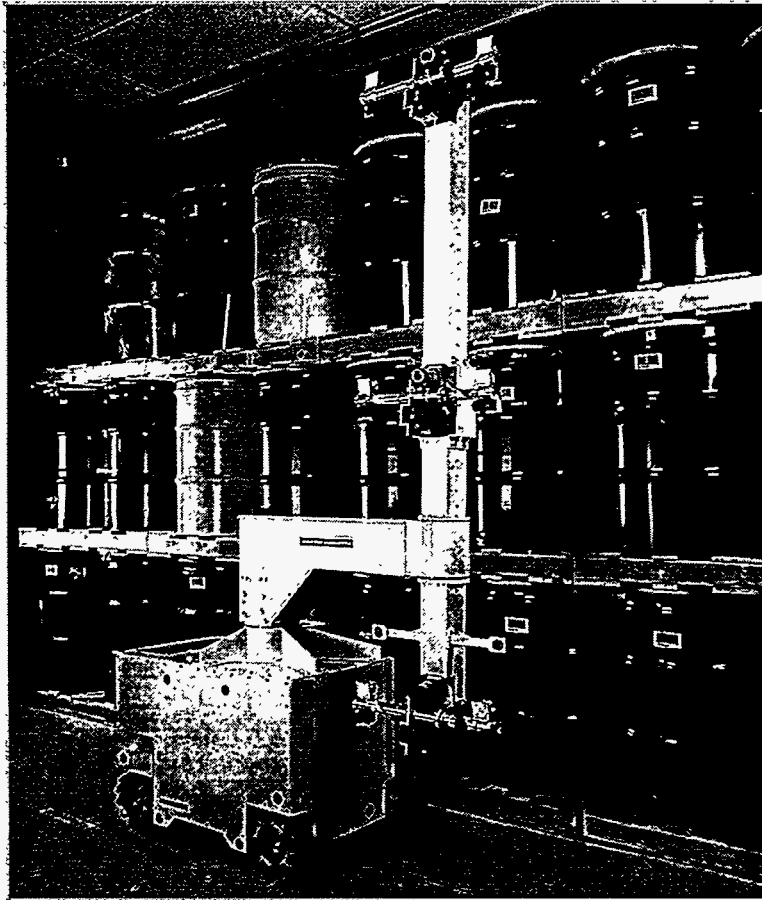
Figure 1-2. Intelligent Mobile Sensing System (IMSS) Phase 2 Vehicle.

1.3 Mission Sensors

Mounted on the sensor mast are three identical integrated sensor suites that gather data to identify and report anomalous drum conditions. A photograph of the lower-level suite is shown in Figure 1-3. This mission sensing system for Phase 2 was designed to detect and report three categories of drum defects: 1) bar code defects, 2) geometric defects, and 3) corrosion defects. Moreover, it is designed to report only *new or changing* defects. For example, each time a drum is inspected, its present condition is compared against a baseline defect list compiled from previous inspections. This trend-based method reduces the amount of data to be stored during an inspection and safeguards against the reporting of false positives.
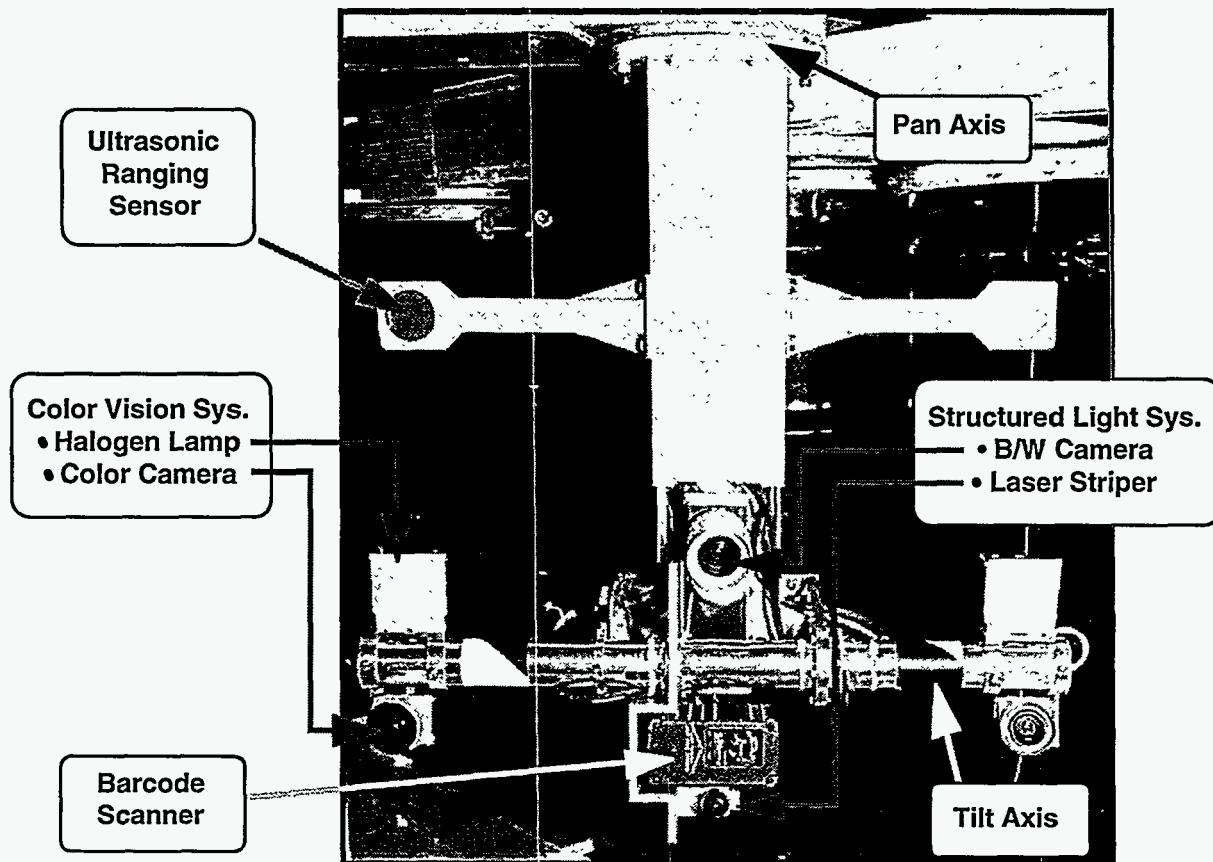
Figure 1-3. Close-up of the IMSS Sensor Mast.

1.3.1 Bar Code Reading

Bar code labels are used to identify and track waste storage drums. A drum's encoded identification label provides positive identification of the drum being inspected and is the unique index to the various databases used for the inspection process. An off-the-shelf bar code scanner/decoder system is used for reading bar coded labels. A scanner head is mounted on each tilt axis, allowing the scanner's laser stripe to be scanned over any portion of a drum face. Decoder units are mounted in the mobility platform and interface with the mission processor through a serial port. Currently, a defect is reported when a drum's bar code label is not read, either because it is missing or it is unreadable due to improper placement or a defective label. With access to a comprehensive drum database containing information such as the class of waste stored in a drum, detailed inventory tracking could also be performed. For example, a defect might be reported when a drum containing "Class A" waste is found to be located in an area designated strictly for the storage of "Class B" waste.

1.3.2 Geometric Defects

Geometric defects include surface dents and drums tilted due to bulging on the bottom or a broken pallet. These defects are detected using a structured light system as shown in Figure 1-3. It consists of a Class IIIb laser striper, a video camera and a frame grabber. As a laser stripe is scanned across the surface of a drum, images are grabbed and sent to on-board image processors to extract the stripe data in real-time. Based on triangulation of the stripe data, a 3-dimensional image of the drum contour is generated and then fitted to a model of a cylinder. Figure 1-4 shows a post-processed plot of a drum's 3-dimensional model fit to a cylinder. The region exposing the underlying cylinder indicates the location of a dent. The angle of tilt is determined from the orientation of the modeled cylinder's major axis. When new defects are found, the parameters of interest are recorded: the location and size of a dent, and/or the drum's angle of tilt.
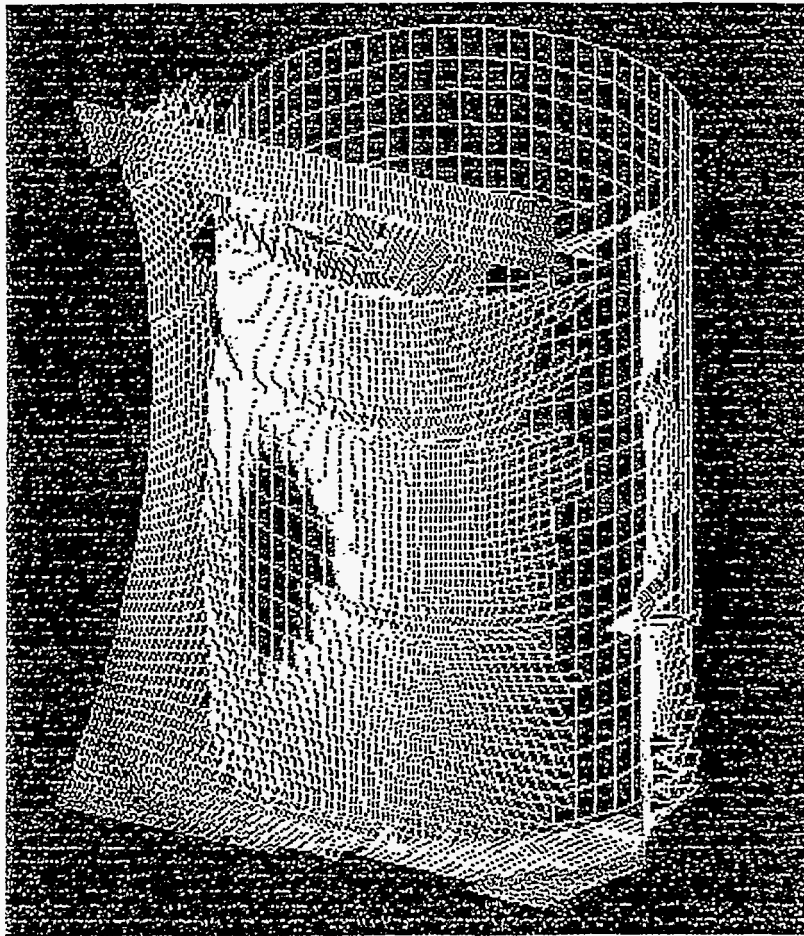
Figure 1-4. Geometric Drum Model.

1.3.3 Corrosion Defects

Corrosion defects include patches of rust, rust streaks, and areas of blistering, chipped, peeling, or missing paint. These defects are detected using a color vision system (see Figure 1-3) consisting of two pairs of color video cameras and halogen lamps. Four to six images of a drum (depending upon drum size) are collected and sent to on-board image processors for color analysis. When new defects are found, size and locations are recorded. Color images of defective drums are stored to a hard disk for later viewing at the operator's control station. Figure 1-5 shows a sample of the processed image that is stored. It is the composite of four images with regions of rust highlighted by red boxes.
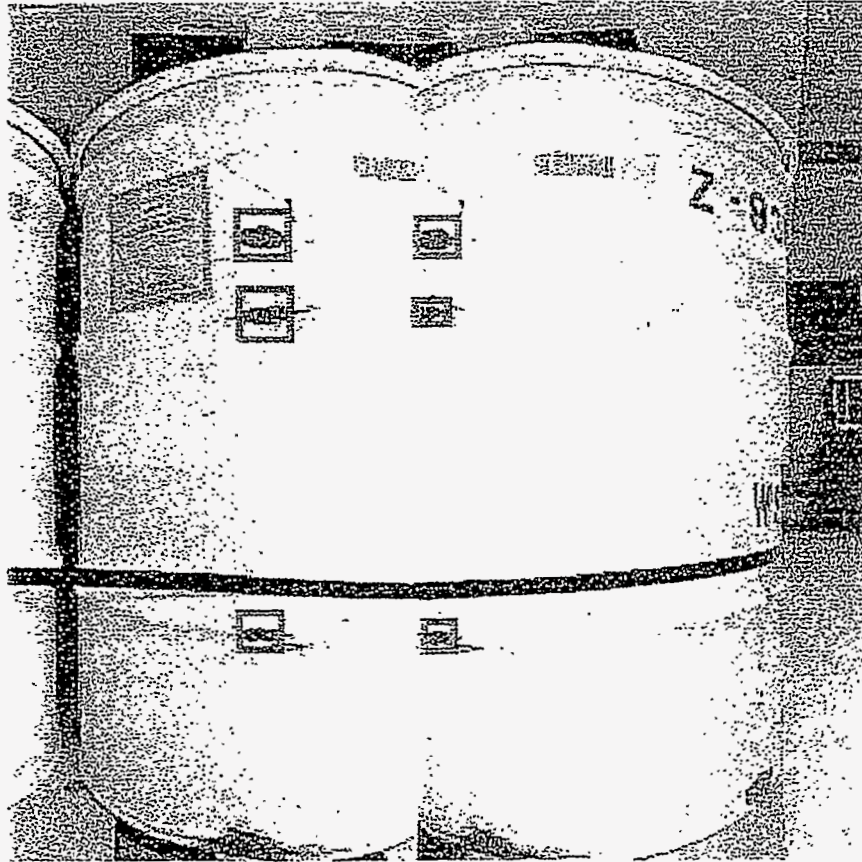
Figure 1-5. Sample Results of Color Vision Inspection.

1.4 Control Station and User Interface

During an inspection mission, all vehicle activity is coordinated by the on-board mission executive software and its real-time planner. However, site personnel are involved to supervise operations before and after a mission. This is done through a graphical user interface from a remote control station. During Phase 2, a full-scale operator interface was developed that provides key interfaces such as *Mission Assignment*, *Mission Assessment*, and *Report Generation*.

Mission Assignment allows an operator to designate the areas of a facility to be inspected, specify the exact sequence of rows, or simply to confirm a default assignment based on the facility's current state of inspection. This interface generates a data file which the vehicle down-loads while docked at its charging station. After the vehicle has received its assignment and is fully charged, at an operator-specified time of day the vehicle departs, inspecting drums until the assignment is completed, or a low state-of-charge condition is signaled. After returning to the charge station, mission results are up-loaded to the control station for subsequent review.

Using the Mission Assessment interface, an operator can review a mission's defect logs, display color images of the defective drums and then generate a report summarizing the mission, along with a list of reported defects and a map of the facility specifying the location of the defective drums. Figure 1-6 shows a sample of the Mission Assessment interface.
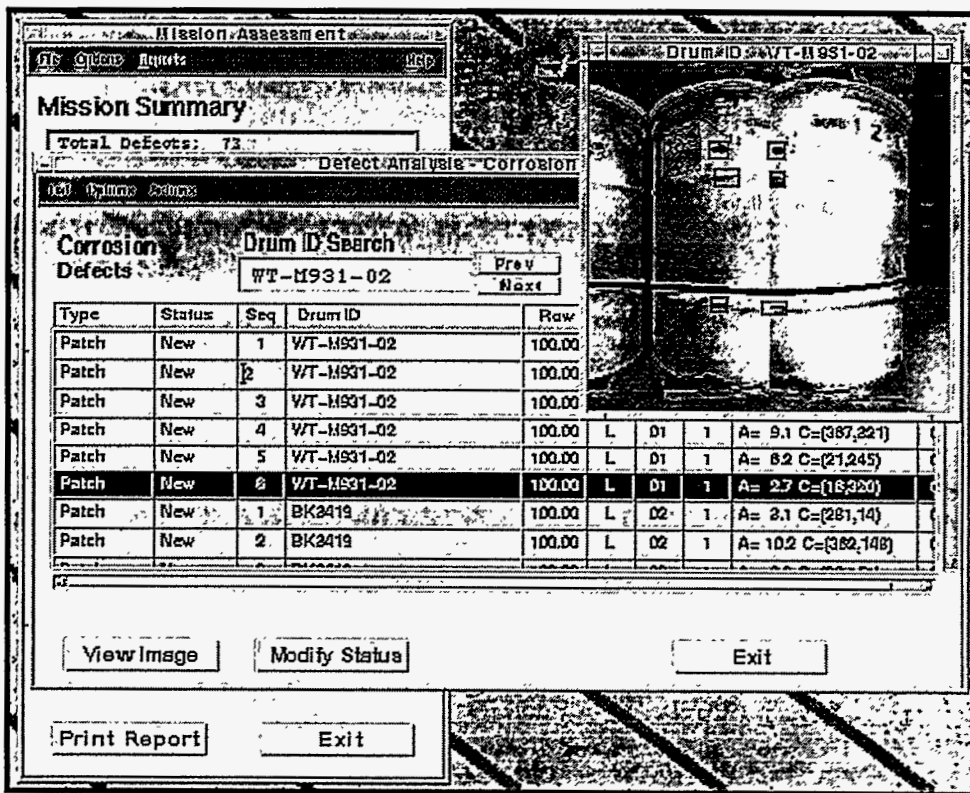
Figure 1-6. Sample of the IMSS Mission Assessment Interface.

2. INTRODUCTION

This report documents basic requirements and background material for the DOE drum inspection problem, and describes the design and evaluation of the IMSS Phase 2 vehicle. The description of basic requirements, background material, and many fundamental design features are retained from the Phase 1 documentation, and have been updated to reflect the Phase 2 vehicle design. Detailed design descriptions also draw on material from the IMSS Phase 2 Preliminary Design Review. Reported performance results and parametric measurements were collected during the end-to-end testing period of Phase 2. The report has the following sections:

- Section 3, "Purpose" describes the DOE application need and discusses system requirements and derived requirements.
- Section 4, "Background" provides additional information both on inspection procedures currently approved by DOE and EPA as well as information on benefits and costs.
- Section 5, "Methodology" is subdivided into four major sections. Section 5.1 summarizes the design process used during Phase 2. Section 5.2 on "System Design" presents the system architecture and subsystem block diagram, and Section 5.3 discusses each subsystem in turn. Section 5.4 on the "Test Facility" describes the facility mockup that was built to provide a test environment for performance measurement.
- Section 6, "Results and Discussion" presents evaluation and performance measurement results for each subsystem of the vehicle, presented in the same order as the subsystems are introduced in Section 5.3. System-level experiments and the Phase 2 demonstration are also summarized.
- Section 7, "Conclusions" summarizes the Phase 2 efforts and the associated performance results, and discusses lessons learned and uncovered issues that should be addressed in Phase 3.

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 the next section. 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 3-1 were developed during Phase 1. Other derived requirements are shown in Table 3-2.

Table 3-1. Functional Requirements.

Automatically generate reports
Minimal operator inputs
Navigate autonomously
Avoid unknown obstacles
Inspection time equal to or better than a human
Inspection performance:
Dents: Detect round or pointed dents (>1")
Tilts: Identify tilted drums
Displacement: Identify missing or displaced drums
Bar Codes: Scan labels; identify missing labels
Rust: Detect, quantify and track surface rust
Streaks: Identify rust streaks
Corrosion: Detect, quantify and track corroded paint

The requirements selected and documented in the system specification (§5.1 and Appendix B) were a lowest common denominator and in general picked the most stressing requirement. This was to ensure broad applicability to all DOE facilities.

Several broad operational goals were used to focus the development of this system:
- build a device that could become a standard system in the sense that it could be DOE and/or EPA certified for these monitoring and inspection processes.
- build a system that was inexpensive to procure, and easy and inexpensive to install and operate
- the system should be easy to operate so that a typical operator or technician could run the system
- the system should be extremely robust in operation in the sense that the system should run in any kind of weather; when the system encounters any anomalies (external physical, or internal system) it should be able to work around them; and the system should never, ever run into anything.
- the system should be simple to maintain and not require any undue effort or unique tools.

Table 3-2. Derived Requirements.

KEY DRIVER	DERIVED REQUIREMENT
Operate in Waste Storage Area	- 20" 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 Contaminated and Hazardous Areas	- design for comtamination control
Safe operation in environment	- 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	- Intelligent vehicle executive - map based planner - realtime sensor based control - sensor based replanning
Detect Anomalous Characteristics	- provide background measurement capabilities for volatiles and radiation - detect rust patches, dents, scratches
Log Locations and Characteristics of Anomolous Measurements	- provide data archiving on board vehicle - transmit to console at mission end - provide navigational measurements to locate of events - archive visual information for anomolous events - provide bar code and label reading system
Characterize Nature of Contaminants for related investigations	- 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	- allow direct operator control of all automous operations as necessary - communication link - supply direct teleoperated control - provide display of vehicle location, site map, measurement data and vehicle status
Generate Inspection and Monitoring Reports	- be able to operate on database to select and correlate desired information - automatically print out reports after inspection
Report Mission Status	- executive planner must record status of its tasks - auto print map and path
Accomodate Future Unknown Tasks	- modular interfaces for additional equipment (data, electrical, mechanical) - extra space on top of vehicle

4. BACKGROUND

4.1 Inspection Procedures

Representative EPA and DOE approved inspection procedures are shown in Table 4-1 and Table 4-2 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 3-1 were developed during Phase 1. 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 drums stored four to a pallet and have pallets stored in single rows. Stacking heights varied from two to five drums with an average of three. Aisle widths varied from 26" 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 drum is required. Operator response to flagged drums is required within 24 hours. All drums must be inspected every six days.

When 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 judgment 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 that 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 drum top, leaking roofs, standing water); if source is from side of drum or 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 drum inspection requirements were incorporated:
- 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 drums,
    - 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 drums includes:
  - white,
  - gray,
  - black,
  - yellow, and
  - silver.
- Visual anomalies NOT to be flagged 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 drum is identified to ensure the condition is corrected within 24 hours.
- A map of the area should be included on which the defective drum 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 4-1. 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 (*i.e.,* 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.*

Table 4-2. Waste Storage Facility Inspection Procedures Extract (Rocky Flats).

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 "NA". Inspections must be performed weekly so that no more than six days elapse between inspections.

1. Is hazardous waste only being stored in authorized areas?					
2. Last inspection within 7 calendar 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. Area containers in good condition?					
10. Is the hazardous waste compatible with container?					
11. Are only approved hazardous wastes being accumulated?					
12. Are the containers closed?					
13. Are containers in a locked fenced area?					
14. Area free of spillage, leakage, or other accumulated liquid?					
15. Is perimeter fence/railing and roof in good condition?					
16. Container label(s) correct, legible, and visible?					
17. Is operating log (or WEMS) current and available					
18. Is there adequate aisle space, which is clear of obstruction?					

Inspect the containers for holes, dents, bulges, rust, damages seams or signs of leakage.
Signs of incompatibility include: bulging, blistering, fuming 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 ACTION
(if additional space is required the reverse side of this logsheet may be used for comments)

_____ DATE _____
_____ DATE _____
_____ DATE _____

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 introduce 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 drums 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 drum without 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 drums 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 verification of each individual drum 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 drums can be examined quicker (in terms of drums 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 drum. 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 / year including costs for wages, overhead (suits, sensors, *etc.*), support (exit exam and decontamination, *etc.*), and training.
- Use of time during an 8 hour shift includes 4 hours for inspection, 1 hour 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, 2 shifts per day.
- Vehicles do not operate on weekends.
- Required support is 30 minutes per trip for 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 / year and automated - $210k / year. The calculated productivity for each system in terms of hours of inspection time are: manned 768 hours / year (52 weeks - 2 weeks vacation - 2 weeks holidays = 48 weeks per year. Weekly productivity is 4 hours / day * 5 days / week - 4 hours / week training = 16 hours / week. Total productivity is 48 * 16 = 768) and automated 3744 hours per year (52 weeks per year; weekly 16 hours / day * 5 days - 8 hours maintenance = 72 hours / week. Total productivity is 52 * 74 = 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 drum, consider the following statements. When a human inspects a drum he must examine his instruments while swiping or pointing them at the drum 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 drums 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 drum. 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 section outlines the design process used during Phase 2, provides an overview of the IMSS system and vehicle design, and summarizes the design of all subsystems.

5.1 Design Process

5.1.1 Engineering Stages

The engineering process model used by the IMSS Phase 2 development team is depicted in Figure 5-1. This careful process was followed to ensure all requirements were met in a consistent and compatible manner.
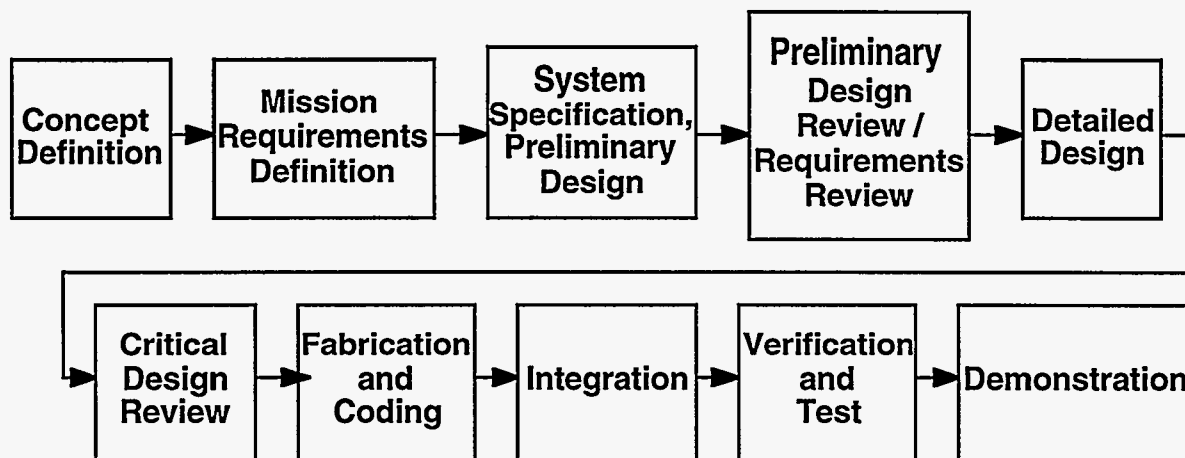
Figure 5-1. Engineering Process Model.

- Concept Definition: This step in the process is documented in the IMSS Phase 1 Report [IMSS Phase 1], and to some extent in Sections 3 and 4 of the current document.
- Mission Requirements Definition: Functional and derived requirements are summarized in Section 3 and current inspection procedures are described in Section 4. From these, a formal technical requirements document, called an A-Level Specification, was derived. This serves as the start of the formal engineering process. This step is discussed more in §5.1.2, and in Appendix B, where the A-Specification document is also included.
- System Specification, Preliminary Design: This step involves trade studies for each major component in each subsystem, and results in a preliminary design. The trade study materials and conclusions are maintained and documented informally by each team member responsible for the respective subsystems. The preliminary design, including summaries of the trade studies, are formally reported in the next step. Each subsystem was further specified with a B-Level Specification which included specific performance parameters for individual components based on the preliminary design. These B-Specs were used to ensure compatibility and consistency between subsystems.
- Preliminary Design Review / Requirements Review: The requirements, trade studies, and preliminary design for every subsystem was systematically covered during the preliminary design review (PDR), attended by a team of experts. Section 5 is largely a compilation of the PDR material [IMSS PDR] and portions of the Phase 1 Topical (Final) Report [IMSS Phase 1] retained in the Phase 2 vehicle design.
- Critical Design Review: A design review was held prior to ordering components (except long lead items) or manufacturing pieces. This internal design review ensured compatibility between all subsystems, and ensured that all internal engineering standards were met.

- Software Development was captured in a Software Development Plan, and with Software Development Folders for each subsystem. These formally structured living documents are maintained by each subsystem lead, and used as a daily log for design, development, and experimental activities. A Software Design Review was held to validate design decisions, and to obtain reusable code and lessons learned from related programs.
- Integration: The project moved next to fabrication, coding, and integration. This period involved manufacturing, subsystem assembly, and system level assembly. Each subsystem was integrated and tested individually, whenever possible, against its A- and B- specs. Software attached to individual subsystems was developed and integrated during this period.
- Verification and Test: Subsystem tests were performed throughout the integration period. Two intermediate assemblies were built: the base vehicle, and the sensor mast. These intermediate assemblies also underwent integration and test. After the final system was integrated, an overall system verification was performed. Performance evaluations were done during an approximately two month period before the final demonstration. These results are documented in Section 6.
- Demonstration: An integrated demonstration of the vehicle performing inspections of the mock facility was given to an audience at the conclusion of Phase 2. This demonstration is also documented at the end of Section 6.

5.1.2 Technical Requirements Derivation

This step began with visits by technical personnel from the IMSS development team to several DOE waste storage facilities, specifically: ORNL, INEL, Hanford, and Rocky Flats. Documentation was obtained for inspection reporting procedures at Hanford and Rocky Flats, and documentation on EPA RCRA was obtained. An independent subcontractor analyzed and interpreted these for operational correctness. Requirements extracted in this step were already discussed in Sections 3 and 4. The IMSS development team generated technical requirements organized into the following categories:
- Environment and facility parameters
  - -- Temperature
  - -- Drum types and configuration
  - -- Accessibility
- Reporting requirements and procedures (operator interface)
  - -- Automatic report generation
  - -- Reporting frequency
- Drum defects (mission sensors)
  - -- Rust, corrosion, dents, rust streaks, barcodes, displaced drums, missing drums, tilted drums
- Operational parameters (vehicle)
  - -- Autonomous operation
- Product oriented
  - -- Safety, Decontamination, Maintainability, and Portability

The team generated a formal technical requirements document, called an A-Level Specification, using the combined knowledge from the site visits, the inspection and reporting procedures, and previous technical experience during Phase 1. The complete "A-Spec" is included in Appendix B. The following major design drivers resulted from the A-Spec:
- Defect size [A-Spec subsection 3.2] DRIVES sensor resolution
- Aisle width [2.3.1] DRIVES view angles, navigation, vehicle footprint
- Inspection rate [3.2] DRIVES number of sensor suites, processing speed
- Building configurations [2.4.1] and dead end aisles [2.5] DRIVE mast height and location
- Temperature range [2.5] DRIVES available equipment and components
- Cost reduction DRIVES use of on-board processing
- Dent detection DRIVES laser power and location, sensor suite and mast configuration, on-board processing requirements
- Barcode location DRIVES power and weight of unit, mast weight
- Rust and corrosion, including many colors of drums DRIVE new inspection algorithms

5.2 System Overview

5.2.1 Physical Components of the IMSS System

The complete IMSS system has three physical components:
- Control Station: A graphical user interface on the control station is used by an operator to command and review inspections performed by the vehicle. The control station can be hosted on most low-end inexpensive UNIX workstations. The control station is used occasionally by administrative personnel for certain functions. A single control station services multiple waste storage facilities, as illustrated in Figure 5-2. (The control station contains a model of each facility, a database of all the drums for each facility, and a database of defects located in each facility.) The control station can be linked to a printer for printing inspection reports, and to a storage unit for automatic archiving of inspection results and data.
- Docking Station: Each waste storage facility contains a docking station, which the vehicle uses to automatically recharge its batteries. Each vehicle communicates with the control station via an ethernet link. (Specifically each vehicle links with its docking station via a radio ethernet, and each docking station is connected to the central control station via a hardwired ethernet.)
- Vehicle: The vehicle automatically drives through the facility and inspects drums, according to inspection commands entered and scheduled by the operator.
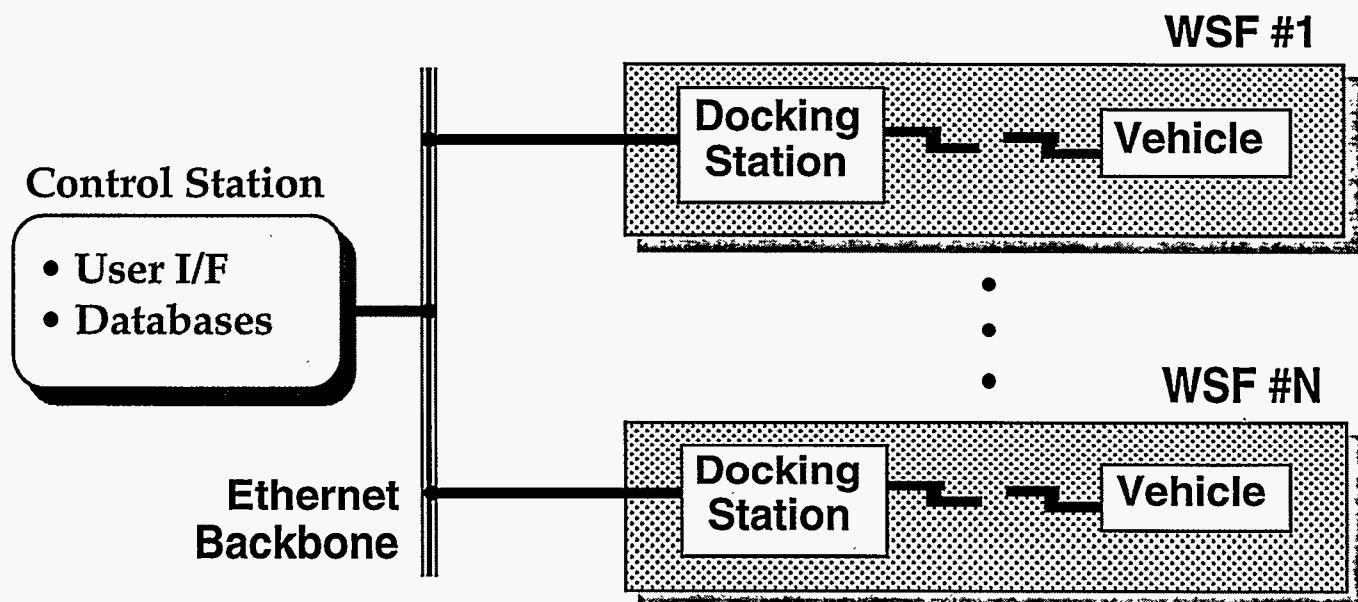
Figure 5-2. Central Control Station Controls Multiple Vehicles in Multiple Facilities.

5.2.2 Functional and Software Architecture

The functional architecture is shown in Figure 5-3. Communication between the control station and vehicle occurs only via file transfers (over the ethernet). The Supervisor subsystem on the operator console downloads a plan file to the vehicle's hard disk. Once the vehicle completes execution of the mission plan defined in that file, it uploads inspection results, including images of defective drums, back to the operator console. Finally, the operator can use the Operator Interface to examine inspection results, print a report, etc.

Control Station

Operator Interface (OPR)
- User Inputs (GUI)
- Graphics/Image Display
- Inspection/Motion Plan Generation
- Mission Simulator
- Report Generation

Supervisor (SUP)
- Mission Assignment
- Mission Assessment
- Safety Validation

WSF Model Manager (WMM)
- Facility Database
- Defect Database
- Mission Sensor Parameters

WSF Model

COTS
- UNIX OS
- Graphics Libs

(Radio E-Net at Docking Station)

Vehicle (VME)

Mission Executive (EXC)
- Mission Sequencer
- Mission Monitor
- Contingency Planner
- Coordinate Mission Sensors M

WSF Model
Defect Log

Navigation System (NAV)
- Navigation and Positioning
- Aisle Following
- Obstacle Avoidance
- Trajectory Generation M

Environmental (ENV)
- Bar Code Scanner I/F
- Gas and Rad. Detectors M

Mobility & Control (MOC)
- Ranging Sensors
- Wheel Kinematics
- Vehicle Health and Safety
- Mast and Pan/Tilt Control
- VME Device Drivers M

Geom. Insp (GIS)
- Locate Drums
- Identify & Record Dents and Tilts D

Corrosion Insp (COR)
- Locate and Classify Rust, Corrosion and Streaks on Drums D

COTS
- VxWorks OS
- VME Device Drivers
- TCP/IP Comm. M

COTS
- 3L DSP Kernel OS
- DSP/Image Processing Libs
- Frame Grabber Functions
- VxWorks Comm. Interface D

M => MVME162 (vehicle)   D => C40 DSP (image processing)

Figure 5-3. IMSS System Software Architecture.

5-4

The functional architecture is based on a standard reference model for automated systems developed by the National Institute of Standards and Technology (NIST), which was subsequently ported to NASA for their space program, used in the IMSS Phase 1 vehicle, and re-implemented for the IMSS Phase 2 vehicle. 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 calls 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 real-time software architecture (on the vehicle) is shown in Figure 5-4. Figure 5-3 showed a high-level overview of the major subsystems in this architecture. In Figure 5-4, each box with rounded edges represents a task (*i.e.*, process) running under the VxWorks operating system on the vehicle's host processor. The label above each box, *e.g.* tPlan, is the name of that task. All these tasks communicate with each other using the message passing facility built into VxWorks. The two primary mission processing subsystems, the corrosion detection system (COR) and the geometric inspection system (GIS), execute on multiple processors: the vehicle host processor (as tasks named tCOR and tGIS), and also on several dedicated DSP processors (not shown in this figure). For each of these subsystems, their host and DSP processors communicate via a message passing system that communicates across the VME bus shared by these processors.

A slightly modified environment is used for development purposes. A simple interactive menu-based program replaces the planner and task dispatcher, and permits the developer to issue individual commands (messages) to any of the other tasks running in the system. This program is purely text-based and is run by remote logging into the vehicle's host processor from a UNIX workstation. The menus for this program are listed in Appendix A to give an idea of the functionality provided. Some subsystems have stand-alone testing programs, which are not part of this central menu-based program.
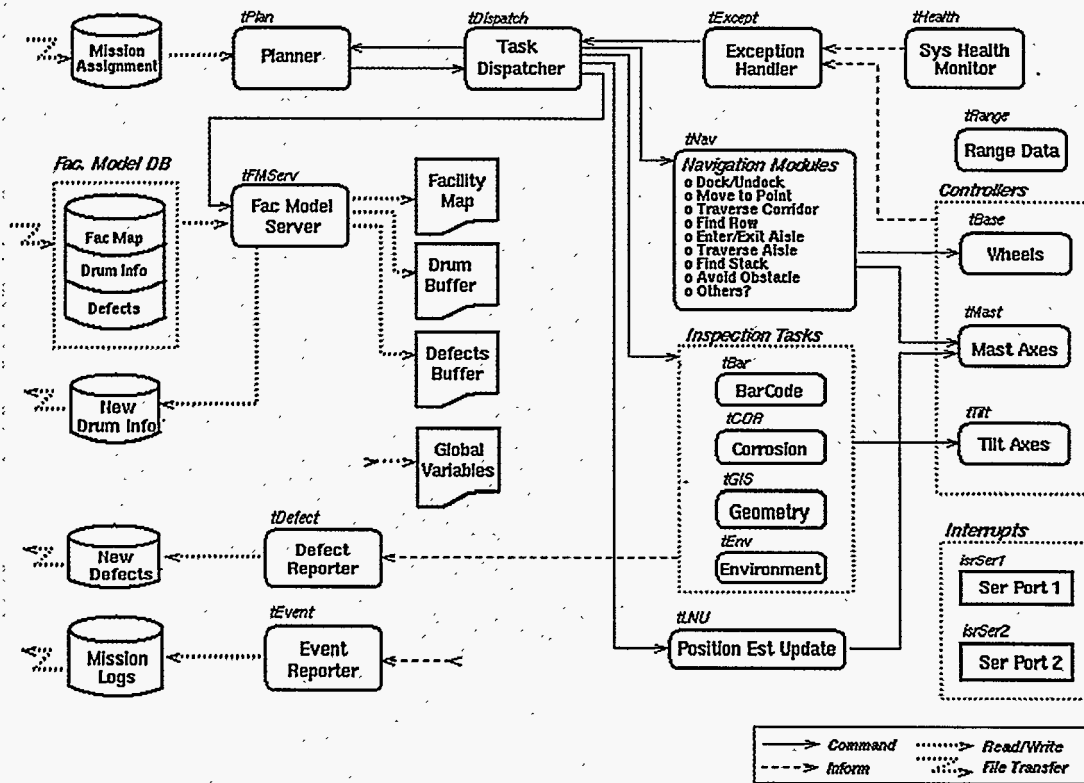
Figure 5-4. IMSS Real-Time Software Architecture.

5.3 Subsystem Designs

5.3.1 Mechanical Subsystems

5.3.1.1 Vehicle Structure

A new vehicle was designed and constructed during Phase 2 to meet the specific requirements of the DOE drum inspection problem. Figure 1-2 in Section 1 shows a photo of the final vehicle. Diagrammatic side and top views of the vehicle are provided in Figure 5-5 and Figure 5-6. Figure 5-7 through Figure 5-11 elaborate the key design issues and resulting design, covering specifically the topics of vehicle width, vehicle length, packaging of vehicle batteries, and the ultimate design layouts of the lower and upper parts of the base.

Figure 5-5. Diagrammatic Side View of Vehicle.

Figure 5-6. Diagrammatic Top View of Vehicle.

AISLE WIDTH (A)	VEHICLE WIDTH (B)	EQUAL VEHICLE SPACING (C)	MAXIMUM SPACING WHEN HUGGING ONE WALL (D)
36 inches	30 inches *	3 inches on a side	5 inches
	24 inches	6 inches on a side	11 inches
30 inches **	24 inches	3 inches on a side	5 inches
	20 inches	5 inches on a side	9 inches
28 inches ***	24 inches	2 inches on a side	3 inches
	20 inches	4 inches on a side	7 inches
26 inches +	20 inches	3 inches on a side	5 inches

* SWAMI design constraint   ** IMSS design constraint   *** Los Alamos Aisle Width   + Rocky Flats Characterization Aisle Width

> **Due to the varying aisle width constraints at the various DOE sites, the design goal for the vehicle should be 20 inches (0.5 m) wide with the worst case being 24 inches (0.61 m).**

Figure 5-7. Vehicle Width Issue.

Figure 5-8. Vehicle Length Issue.

Figure 5-9. Vehicle Packaging Issue.

5-8 Vehicle Length Issue

A. CHANGING AISLES

2 m (78.75 in)

30 inches

TOP VIEW OF THE VEHICLE — 20-24 inches

24-75 inches

B. MAKING A U-TURN

2 m (78.75 in)

30 inches

NOTE: An Omni-wheeled vehicle can turn in place and thus the 2 m free space at the end of an aisle can accomodate a 75 inch long by 24 inch wide vehicle.

For the worst case, the vehicle will be 20-24 inches wide and 24-75 inches long depending on the vehicle's turning mode. The optimum vehicle shape would be a square (24 "x 24"), but the shortest length vehicle that is practical is desired.

5-9 Vehicle Packaging Issue

(A) *   28.0"   22.5"
(B)   30.75"   22.5"
(C) **   20.50"   21.5"
(D) **   26.0"+   21.5"
(E)   30.75"   21.5"

(F) **   32.75"   20.5"
(G)   34.25"   20.5"
(H)   37.50"   16.75"
(I) *   30.75"   25.75"+
(J) **   30.0"   16.75"

225 x 0.8 mecanum wheel

260 x 190 Saft Nickel-Cad Battery (B)

reserved for wheel actuators

* - only three batteries & two must be placed on upper level
** - only four batteries & one must be placed on upper level
\+ - assuming a nominal actuator enclosure

Our selection criteria for the vehicle's form is based on it's overall width, design symmetry, the practical implementation of the wheel actuators in their reserved spaces, and being able to accomodate all five batteries on the same lower level if possible. As a result of this trade, we have chosen layout F as the baseline.

Lower Base Design

The IMSS Phase 2 base will be 20.5 in. wide by 32.75 in. long by 24 inches tall. It will have an upper level for electronics and one battery and a lower level for the remaining batteries and actuators. Ground clearance is 3.5 inches.

Figure 5-10. Lower Base Design.

Figure 5-11. Upper Base Layout.

The vehicle must also be able to fit through doors in any waste storage facility. The vehicle width is not an issue here, but the height of the mast could be. However, the IMSS vehicle design incorporates a mast hinge (Figure 5-12) that permits the mast to be easily lowered so the vehicle can pass within any expected door.

The sensor mast of the vehicle is designed so that each of three sensor suites can simultaneously view all the drums in a stack, as shown in Figure 5-13. The vehicle was designed to permit a mast extension, not shown here, which enables the vehicle to inspect four-high stacks. All sensor suites on the mast have identical design, using the layout shown in Figure 5-14.

Vehicle stability is a critical issue. The IMSS vehicle is designed to be stable on slopes up to 17 degrees. Figure 5-15 and Figure 5-16 sketch the analysis that arrived at this value.
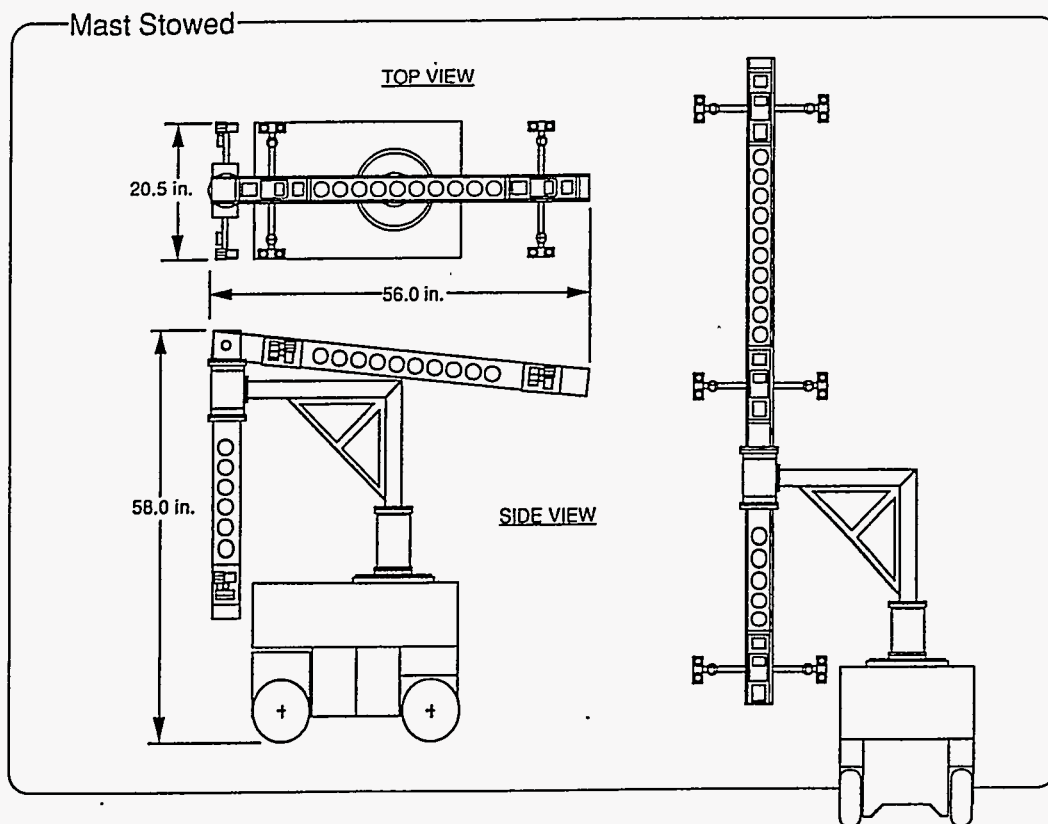
Figure 5-12. Hinged Mast Design for Easy Transport.
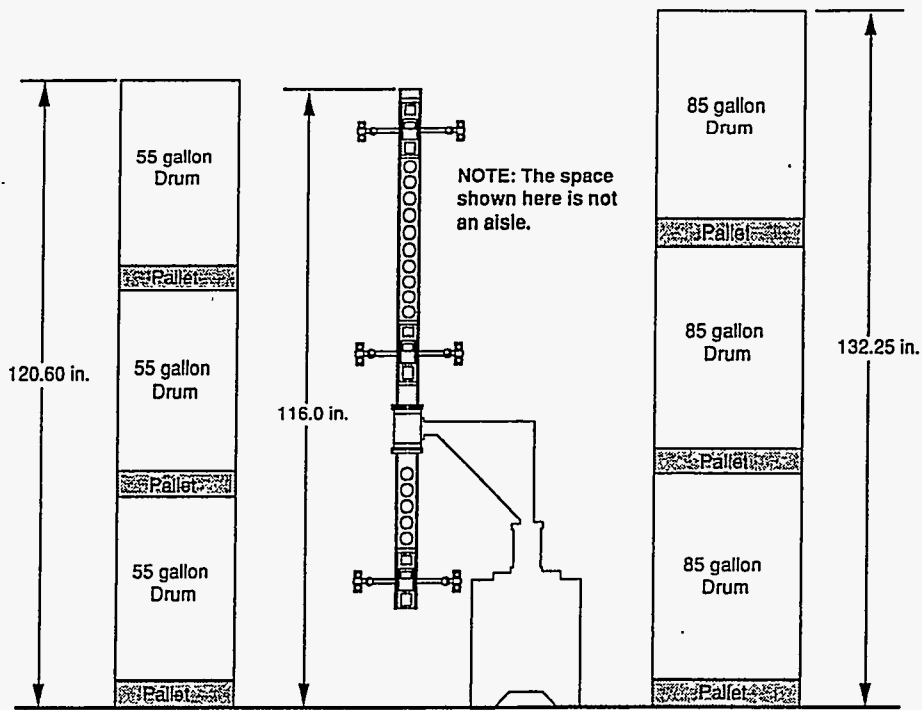
Figure 5-13. Mast Height with respect to 55 and 85 Gallon Stacked Drums.
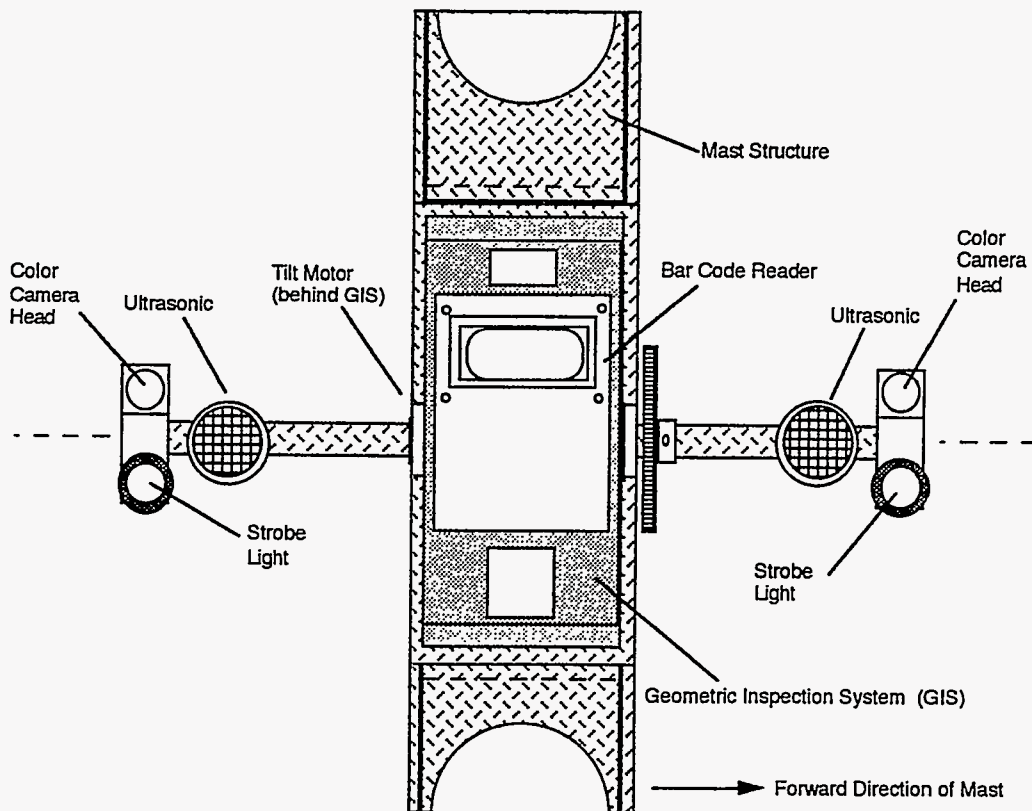
Figure 5-14. Sensor Suite Layout.

Weight Statement

ELECTRONICS	QTY	Weight (Lbs.)
Mission Processor	1	
Motion Control Boards	3	[included
A/D and D/A	3	in electrical
Counter	1	rack weight]
Image Processor	2	
Mass Storage	1	

VEHICLE STRUCTURE	QTY	Weight (Lbs.)
Wheels	4	35.2
Frame (C-S)	1	28.5
Skin (Al)	X	55
Slide Mounts	2	3
Fasteners	X	2
Gearhead Actuators	4	60
Wheel Bearings	4	4
Body Roll Bearing	1	1.5
Misc. Machined Parts	X	20

MISSION SENSORS	QTY	Weight (Lbs.)
Color Camera & Lens	6	9
Landmark Camera	1	1
B & W Camera	3	(included)
Laser Striper	3	24
Mission Strobe	6	6
Landmark Strobe	1	1
Bar Code Scanner	3	10

VEHICLE SENSORS	Qty	Weight (Lbs.)
Ultrasonics	21	
Battery Monitor	1	
Amp Overcurrent	1	3
Watchdog Timer	1	
Other	1	

MISCELLANEOUS	Qty	Weight (Lbs.)
Electric Fan	4	2
Battery Charger	1	4.8
Wire	X	} 15
Elec. Connectors	X	}
Electrical Rack	2	15
Ground Strap	1	5
Batteries	5	257
Power Contacters	2	10

MAST	QTY	Weight (Lbs.)
Sensor Mount	3	2
Elbow Actuator	1	15
Pan Actuator	1	15
Tilt Actuator	3	15
Upper Mast Structure	1	8
Lower Mast Structure	1	4
Elbow Structure (Al)	1	23
Base Interface (Al)	1	15

The total weight of the IMSS Phase 2 vehicle is 669 pounds.

Vehicle Stability Issue

Note: Forward motion of the vehicle is very slow during the inspection cycle and tip over stability is shown here for the static case.

WORST CASE LATERAL STABILITY

A 5.6 inch tall obstacle under one wheel will cause the vehicle to tilt 17 ° and tip over in the lateral direction.

95 lbs.   38 lbs.

∂ = 17 ° (worst case)
∂ = 19 ° (mast constrained within the width of the vehicle)

536 lbs.

WORST CASE LONGITUDINAL STABILITY

A 8.1 inch tall obstacle under one wheel will cause the vehicle to tilt 20° and tip over in the longitudinal direction.

95 lbs.   38 lbs.

∂ = 20 ° (worst case)

536 lbs.

The vehicle will be unstable and tip over on a 17 degree slope or when one wheel rolls over a 5 inch tall obstacle, depending on the location of the mast.

5.3.1.2 Motion Platform

Three degree of freedom Cartesian vehicle motion (x, y, phi) is achieved by using four independently driven omnidirectional 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, is much more accurate, and is safer because of greater controllability. Also, simple Cartesian path planning may be used to position the vehicle precisely.

Mecanum Wheels. The Mecanum omnidirectional 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, phi) vehicle motion is achieved.

Wheel Drive Train. Each wheel is driven by a motor and gearhead through a belt transmission with a 50:1 reduction. Wheel position sensing for control is provided by 1024 count per revolution incremental position encoders with index pulses, which are mounted at the motor. The encoder outputs are decoded using a standard quadrature state method built into the motion control boards, effectively quadrupling the encoder resolution. Motion control is provided by Galil motion control boards (PID control), which drive PWM amplifiers, which drive the motors.

5.3.1.3 Sensor Mast and Sensor Suites

The sensor mast contains an elbow and a pan joint (Figure 5-11) that both rotate about vertical axes and are used to position the sensor suites on the mast so they face a drum from a specified outward offset distance. The mast contains three sensor suites (Figure 5-14) mounted opposite each of the three drum levels. Each sensor suite contains a tilt axis that can tilt the sensors in that suite up and down so the sensors can view the full vertical extent of each drum. Each sensor suite includes two color cameras with halogen lamps, a black and white camera with a laser light strip projector, and a bar code scanner.

Motion Control. The motion control system for the two mast joints and the three sensor suite tilt axes is similar to the wheel motion control system, except that the motors have no further reduction after the gearhead, and lower-power PWM amplifiers are used.

5.3.2 Electrical Subsystems

5.3.2.1 Vehicle Electronics

The control electronics package consists of a VMEbus card cage, motor actuators, and system sensors as shown in the overview diagram in Figure 5-17, and the more detailed diagram, Figure 5-18.

```
┌─────────────────────────────────────────────────────────────────────────┐
│  ┌─────────────────────────┐            ┌─────────────────────────┐       │
│  │ VME Chassis             │            │ Mission Sensors         │       │
│  │ • Mission Processor     │ ◄────────► │ • COR                   │       │
│  │ • Image Processors      │            │ • GIS                   │       │
│  │ • Servo Controllers     │            │ • Bar Code              │       │
│  │ • I/O                   │ ◄──┐       └─────────────────────────┘       │
│  └─────────────────────────┘    │       ┌─────────────────────────────┐   │
│                                  └───────│ Custom Electronics Chassis  │   │
│                                          │ • Mast Axes Amplifiers      │   │
│                                          │ • Safety Board              │   │
│                                          │ • Ranging Sys Electronics   │   │
│            Line-Replaceable Units        │ • SCSI Disk                 │   │
│                                          └─────────────────────────────┘   │
└─────────────────────────────────────────────────────────────────────────┘
   ┌─────────────────────┐               ┌─────────────────────────┐
   │ Actuators           │               │ System Sensors          │
   │ • Amplifiers        │               │ • Safety                │
   │ • Motors            │               │ • Range                 │
   │ • Sensors           │               │ • Battery Parameters    │
   └─────────────────────┘               └─────────────────────────┘
```
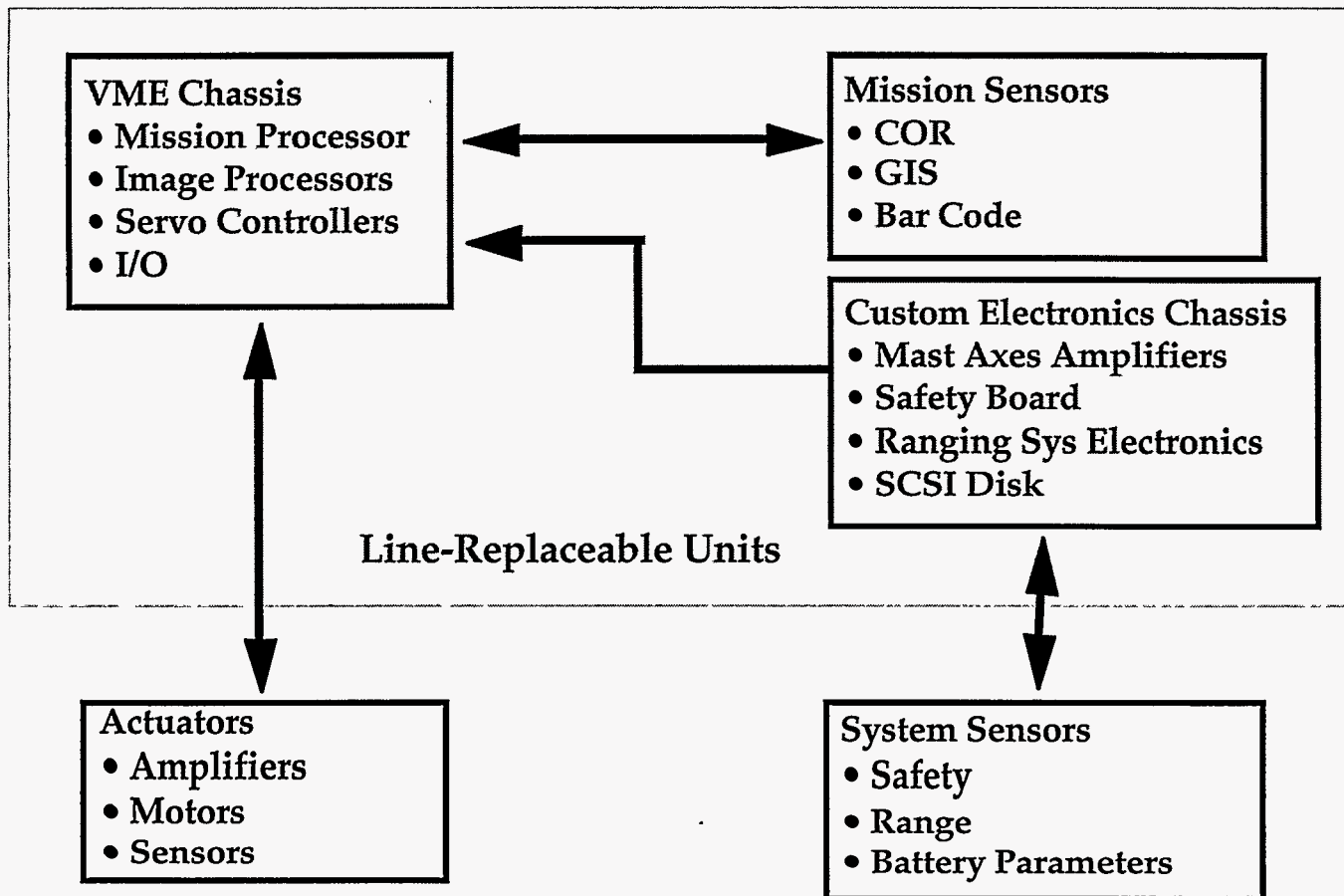
Figure 5-17. Control Electronics Overview.
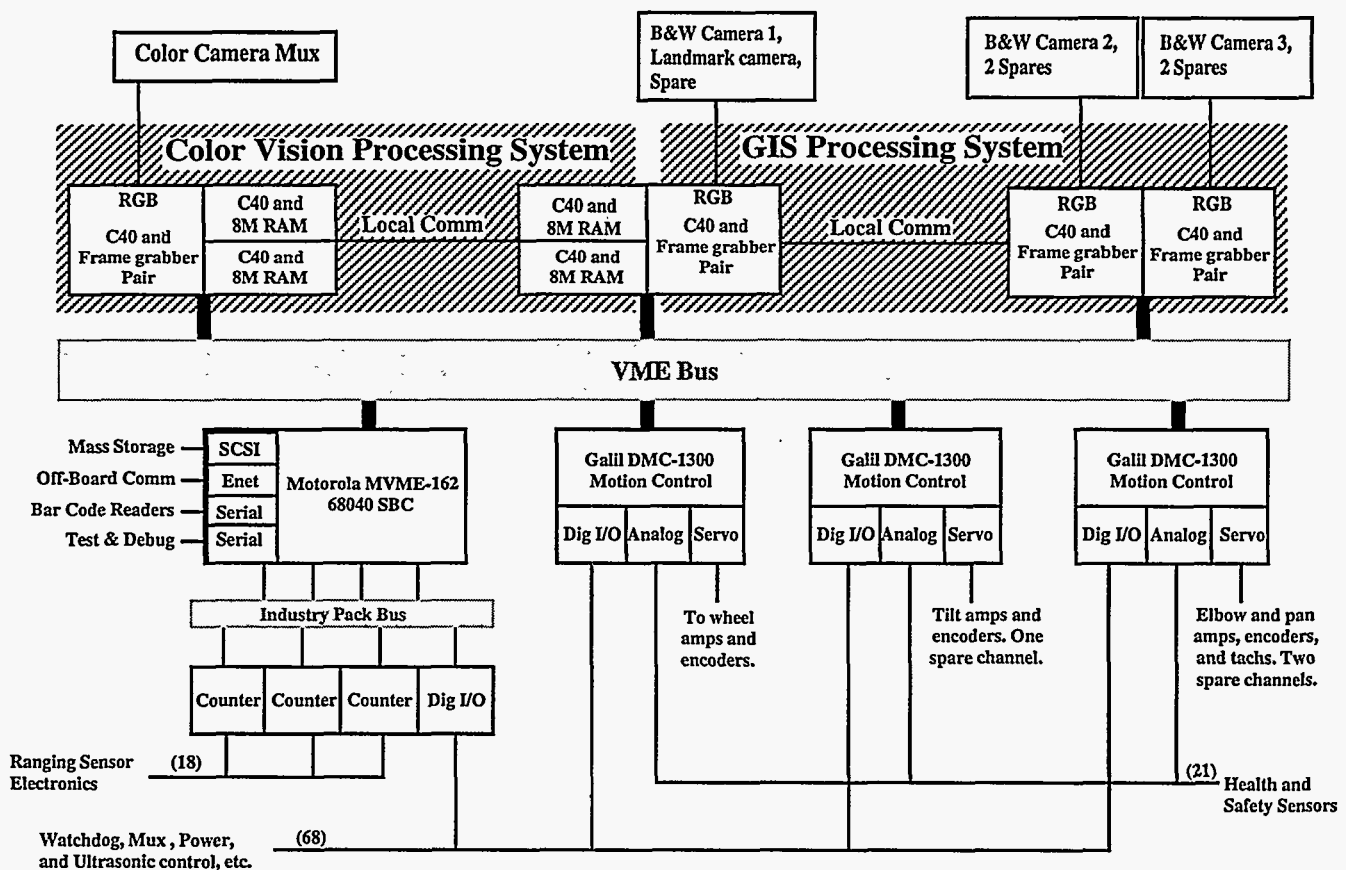
Figure 5-18.   Control Electronics Detail.

The VMEbus card cage contains commercially available boards, including a Force 162 (68040) single board computer, three Galil motion control boards, and five C40 motherboards.

The Force 162 single board computer is connected to a 500 Mb hard disk, an Ethernet connection, and four Industry Pack (IP) Bus daughter boards for digital I/O and counters. System digital discretes are controlled and monitored by the IP Bus digital i/o. These signals are used for power state control for system components, monitoring of abort conditions, and other system functions. The IP Bus counter boards interface to the ultrasonic ranging system. One 16-bit up counter is used as an event counter to acquire the distance to objects for each of the ranging sensors.

Motion control is provided by three four-axis Galil motion control boards. These boards provide adjustable PID controllers for the wheel, mast, and tilt motors, as previously described.

Two of the C40 motherboards are used by the geometric inspection system, and the other three are used by the corrosion inspection system.

5.3.2.2   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.

Numerous ultrasonic sensor modules are located around the vehicle perimeter. The electronics configuration is shown in Figure 5-19. 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 related to the distance of the object that caused the echo.
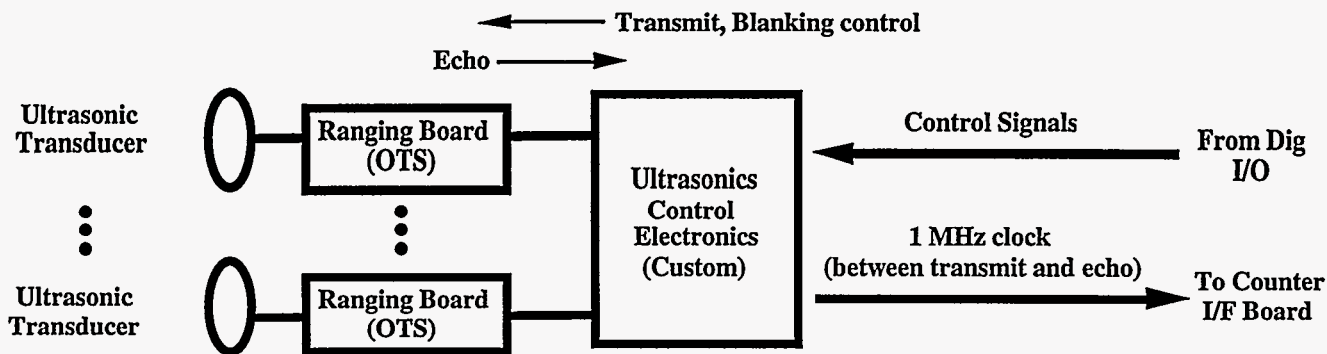
Figure 5-19. Ultrasonic Ranging System Electronics.

5.3.2.3 Communications

All on-vehicle inter-board communications above the hardware control level were implemented using the message passing system built into VxWorks, or a vendor-supplied message passing system that links VxWorks with the C40 DSP boards over the backplane. Communications with the control station uses TCP/IP protocols on Ethernet. Radio ethernet is used in the application, but a thin wire ethernet is more commonly used during development.

5.3.2.4 Power

The key components of the power subsystem are summarized in Figure 5-20. Power is supplied to the vehicle from two sources. The primary power source is a set of 40 NiCad battery cells that combined nominally provide 4.08 kWH at 48 V. The 48V bus supplies the necessary input power for the drive amplifiers, and for DC-DC converters which provide the vehicle system with +5 and ±12 VDC.

The secondary power source is two parallel 28V 12A linear DC power supplies. These external power supplies charge the batteries when the vehicle is off, or trickle charge the batteries during intermittent operations. They are connected to the vehicle battery via a 75 foot tether consisting of three 12 AWG Power/Ground pairs. This allows a maximum inductive and resistive (IR) drop of 1.3V in the tether, which 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.

Externally mounted charge plates on the vehicle's back side provide the electrical connection between a docking station (containing a power supply) and the vehicle's batteries. These charge plates were not used during Phase 2 since an appropriate high-power power supply was not available.
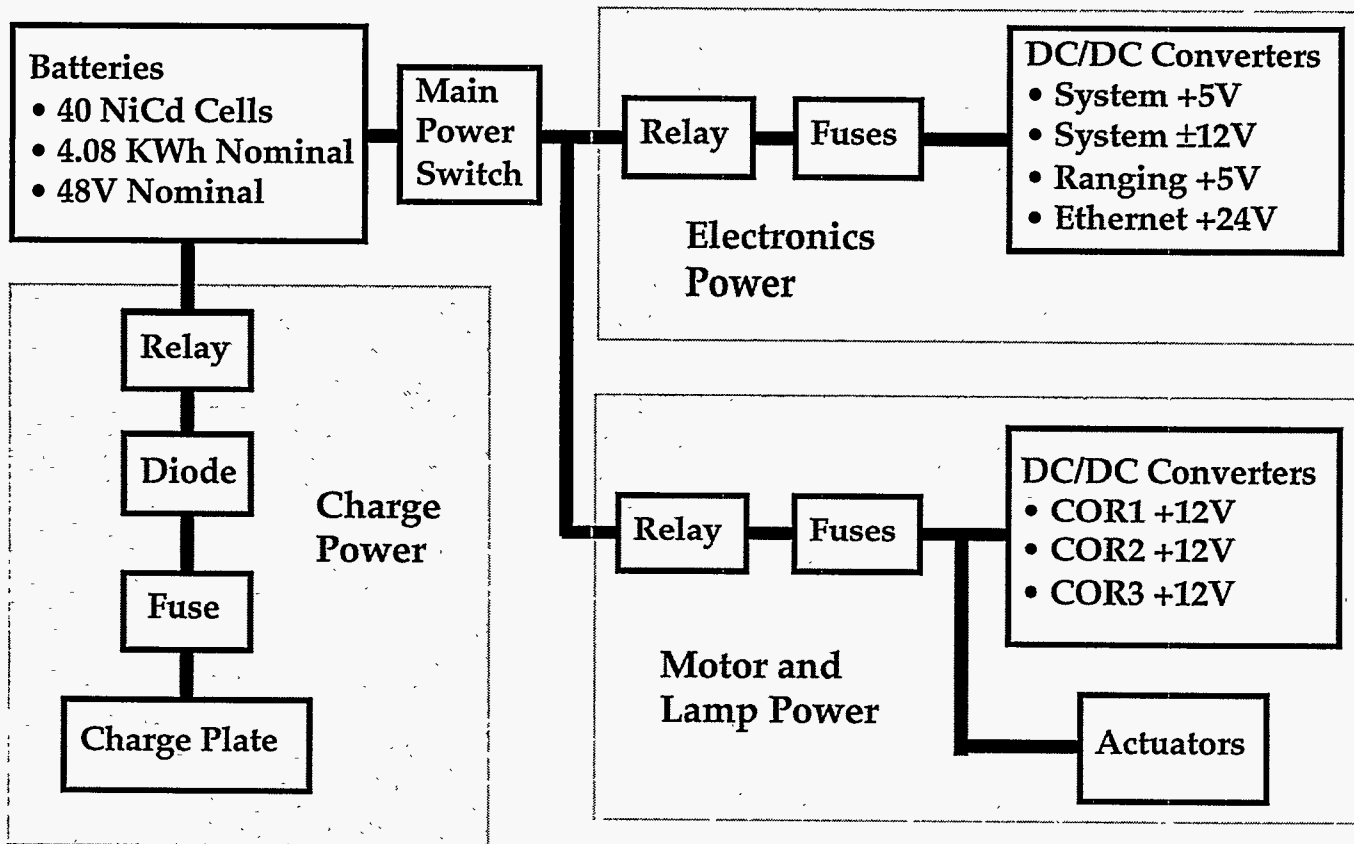
Figure 5-20. Power System Overview.

5.3.3 Safety System

A number of safety measures, both software dependent and hard-wired devices, were implemented and verified for the vehicle. Figure 5-21 summarizes the key components of the safety system.

Software Dependent

Mission Processor	Battery Monitor
• Heartbeat Generation	• Temperature
• Servo Error Monitoring	• Voltage
• Collision Avoidance	• Current

Safety Electronics	Power System
	• System Pwr Control
	• Amplifier Inhibits
Safety Sensors	• Actuator Pwr Control
• Manual Kills	• Fuses and Diodes
• Contact Sensors	
• Limit Switches	

Hard-Wired
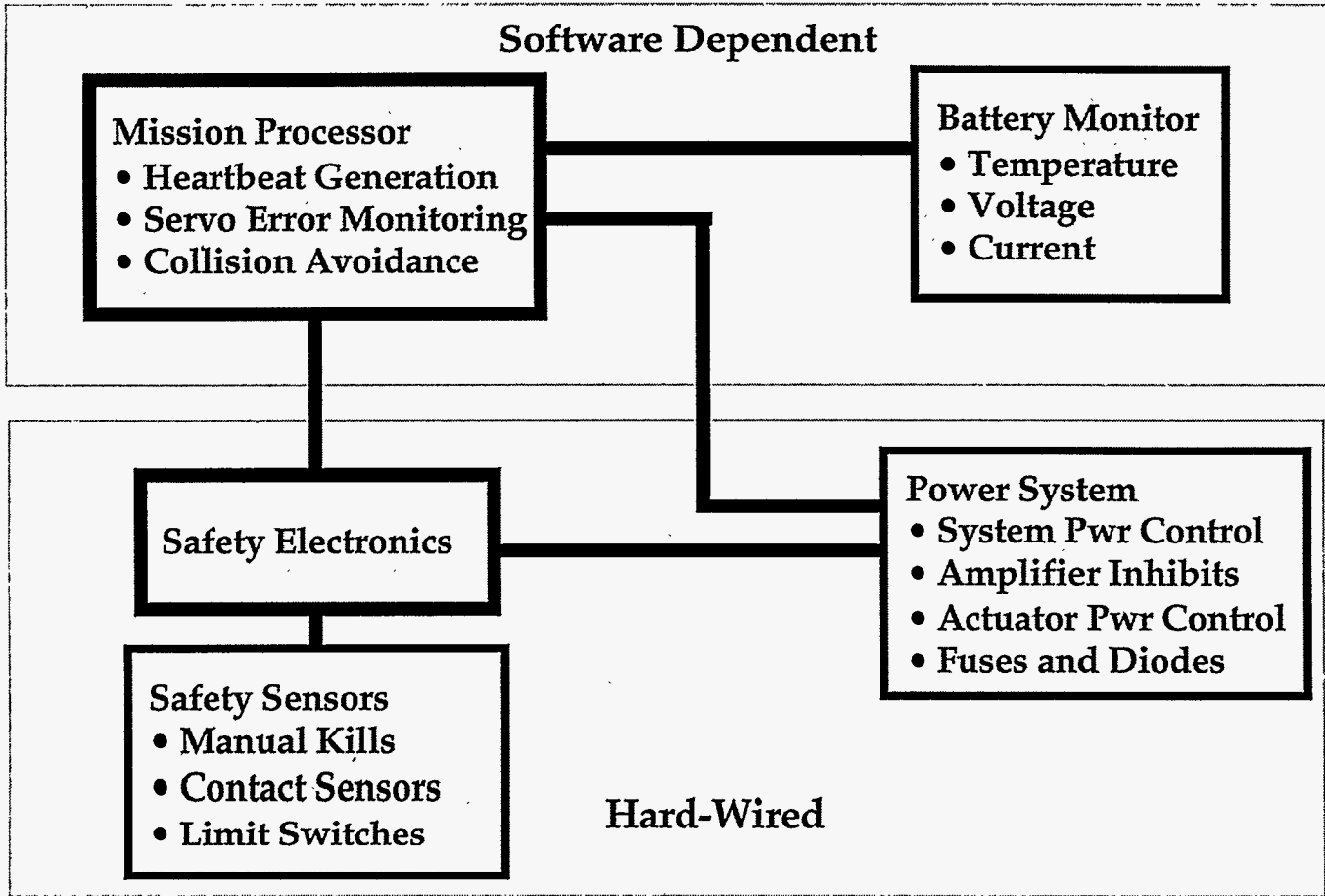
Figure 5-21. Safety System Block Diagram.

5.3.3.1 Passive and Designed-In Safety

Exposure to high battery power. To prevent accidental exposure to the vehicle battery power, "hot-points" are isolated by physical barriers as much as possible. For instance, when all of the vehicle skins are in place, battery power is not accessible and when other panels are removed, any hot-points are isolated by protective plexiglass enclosures. For automatic battery charging via the externally mounted charge plates, voltage at the plates is controlled through the charging relay, which in turn can only be closed through a software-driven discrete. See Table 5-1.

Table 5-1. Charging Plate Safety Verification.

Charging Relay State	Battery Voltage	Charging Plate Voltage
Closed (0.02 Ohms)	+48.5 V	0.0 V

Structured-light sensor laser element. The structured-light sensor contains a Class IIIb laser product which must be operated with special precautions. To mitigate the risk of exposure to these lasers, power to the lasers is controlled through a safety panel key-lock and software-controlled discretes which ensure the lasers are turned on only when scanning to collect data during a drum inspection sequence. Also, the laser element is permanently attached to a beam spreader that reduces the energy density to a class II level within eight inches so that safety is virtually ensured as long as you are eight inches away when the vehicle is powered.

5.3.3.2 Emergency System Power-Down

One of the highest priority tasks running aboard the mission processor during vehicle operation is the System Monitor task. Its primary task is to monitor critical parameters associated with the battery sensor system including: 1) battery voltage, 2) battery current, 3) battery temperature, and 4) the batteries' current state of charge. When one or more of the user-specified safety thresholds is exceeded, the System Monitor alerts the other mission processor tasks, allowing them time to gracefully exit, and then removes all power to the vehicle system by closing the main battery power relay. Once closed, the main relay is re-opened via the safety panel's "Master Reset Switch." Table 5-2 summarizes the causes and effects for an emergency system power-down.

Another condition which will initiate a system power down is the mission processor's heartbeat monitor, which must be asserted every frame. If not asserted, the main battery power relay is opened.

Table 5-2. Emergency System Power-Down Verification.

Cause *	Threshold	Power-down Initiated
High Battery Voltage	62.5 V	Yes
Low Battery Voltage	44.0 V	Yes
High Battery Current	100 A	Yes
High Battery Temperature	27 °C	Yes
Low Battery Temperature	-17 °C	Yes
High Battery Temperature Change	+4 °C	Yes
Low Battery State of Charge	2 %	Yes

* Some Conditions Were Artificially Created.

5.3.3.3 *Emergency Actuator Disable*

These safety measures ensure that under certain conditions, all power to the actuator amplifiers (wheels, mast pan, and mast tilt axes) is removed, effectively inhibiting their operation. These include several hard-wired mechanisms, summarized in Table 5-3: 1) the manual mushroom button kill switch located on top of the mobility platform, 2) the manual kill switch pendant attached to the safety panel kill switch port (used during testing and development only), 3) pressure sensitive contact sensors mounted between the vehicle's skin panels and its structural frame, and 4) limit switches mounted on the mast pan axes and sensor suite tilt axes. These amplifier inhibits may also be initiated through software control. Once initiated, the amplifier inhibits are removed through the safety panel "reset" button, or optionally, through a software driven test menu.

Table 5-3. Emergency Actuator Shut-Down Cause and Effect Verification.

Cause	Shut-down Initiated
Manual: Mushroom	Yes
Manual: Pendant	Yes
Skin-mounted Contact Sensors	Yes
Mast & Tilt Axes Limit Switches	Yes
Software Control	Yes

Servo-control anomalies. Servo-control of each motion axis is accomplished through commercial analog motion control boards which are integrated with a number of safety features. Primary among these is the detection of excess servo errors, caused, for example, by the failure of a position encoder. If an excess servo error is detected, the motion control board disables commands to the actuator amplifier, effectively inhibiting its operation. User-specified servo error thresholds were implemented on each axis, tested and confirmed to perform as designed.

5.3.4 Control

5.3.4.1 Vehicle

Vehicle movement is nominally commanded in Cartesian coordinates (x, y, phi) via autonomous point to point position commands. Velocity commands are also available, but not typically used. 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 5-22 shows the 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.

$$
\underline{x} = \begin{bmatrix} x \\ y \\ \phi \end{bmatrix}
\qquad
\underline{v} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix}
\qquad
\underline{\omega} = \begin{bmatrix} \omega_{FL} \\ \omega_{FR} \\ \omega_{BR} \\ \omega_{BL} \end{bmatrix}
$$
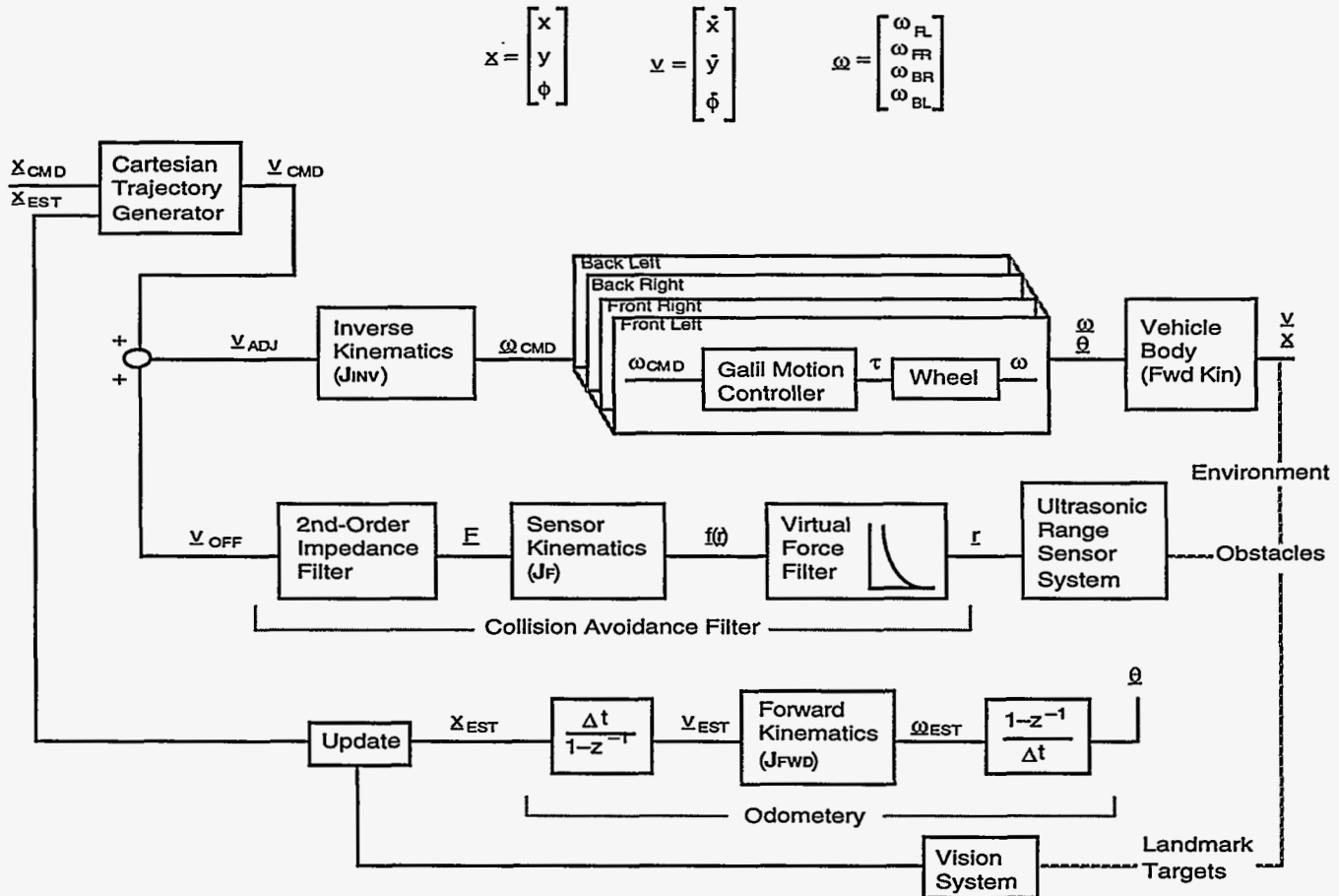
Figure 5-22. Vehicle Motion Control Block Diagram.

5-21

Vehicle inverse kinematics determine wheel velocities for desired vehicle motion as follows:

$$\underline{w} = \mathbf{JINV} \ \underline{v} \qquad (1)$$

The wheel and Cartesian vehicle velocity vectors are:

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

The inverse Jacobian is:

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

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. Vehicle velocity and acceleration limits of 0.4 m/s and 0.2 m/s^2 respectively are used.

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 built up due to wheel slippage and other sources is periodically eliminated by establishing absolute position using the ultrasonic sensors.

Vehicle forward kinematics determine vehicle motion given wheel velocities as follows:

$$\underline{v} = \mathbf{JFWD} \ \underline{w} \qquad (4)$$

The forward Jacobian is:

$$\mathbf{JFWD} = \frac{r_w}{4} \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & -1 & 1 \\ \dfrac{-1}{l_a+l_b} & \dfrac{1}{l_a+l_b} & \dfrac{1}{l_a+l_b} & \dfrac{-1}{l_a+l_b} \end{bmatrix} \qquad (5)$$

5.3.4.1.1 Obstacle Avoidance Filter

A collision avoidance mechanism is provided to prevent contact with unknown or out of position objects. Ultrasonic range sensors located around the vehicle perimeter, as illustrated in Figure 5-23 for the old Phase 1 vehicle, 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.

The virtual force filter outputs a virtual sensor force vector:

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

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

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

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

The sensor kinematics transforms virtual force coordinate frames as follows:

$$\underline{F} = \mathbf{J_F} \, \underline{f}(r) \tag{8}$$

The Jacobian combines and transforms virtual forces from sensor frames to the vehicle frame:

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

The parameters for the sensors (eight on the old Phase 1 vehicle) 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	+	+	

The virtual forces, resolved in the vehicle reference frame are:

$$\underline{F} = \begin{bmatrix} F_X \\ F_Y \\ T_F \end{bmatrix} \qquad (10)$$

An impedance filter uses difference filters that convert virtual forces into commanded velocities as follows:

$$^v X_{OFF_k} = a_{xy}\,^v X_{OFF_{k-1}} + g_{xy}\,^v X_{OFF_{k-2}} + h_{xy}\,(F_{X_k} - F_{X_{k-1}}) \qquad (11)$$

$$^v Y_{OFF_k} = a_{xy}\,^v Y_{OFF_{k-1}} + g_{xy}\,^v Y_{OFF_{k-2}} + h_{xy}\,(F_{Y_k} - F_{Y_{k-1}}) \qquad (12)$$

$$^v f_{OFF_k} = a_f\,^v f_{OFF_{k-1}} + g_{xy}\,^v f_{OFF_{k-2}} + h_{xy}\,(T_{F_k} - T_{F_{k-1}}) \qquad (13)$$

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

$$a_n = \frac{2\,J_n + B_n\,Dt}{J_n + B_n\,Dt + K_n\,Dt^2} \qquad (14)$$

$$g = \frac{-J_n}{J_n + B_n\,Dt + K_n\,Dt^2} \qquad (15)$$

$$h = \frac{Dt}{J_n + B_n\,Dt + K_n\,Dt^2} \qquad (16)$$

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 x,y and rotation f.

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.

A collision avoidance system implemented using the collision avoidance filter provides two modes of operation. The first mode provides 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 most useful for contouring around large obstacles in free-space areas. The second mode provides vehicle motion corrections in x and y only. Virtual torques are ignored, so no rotations are possible.

·5.3.4.2 Sensor Mast and Sensor Suites

Scan platform motion is controlled via pan and tilt angular position commands with associated acceleration and rate limits. The Galil motion controllers described previously 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.
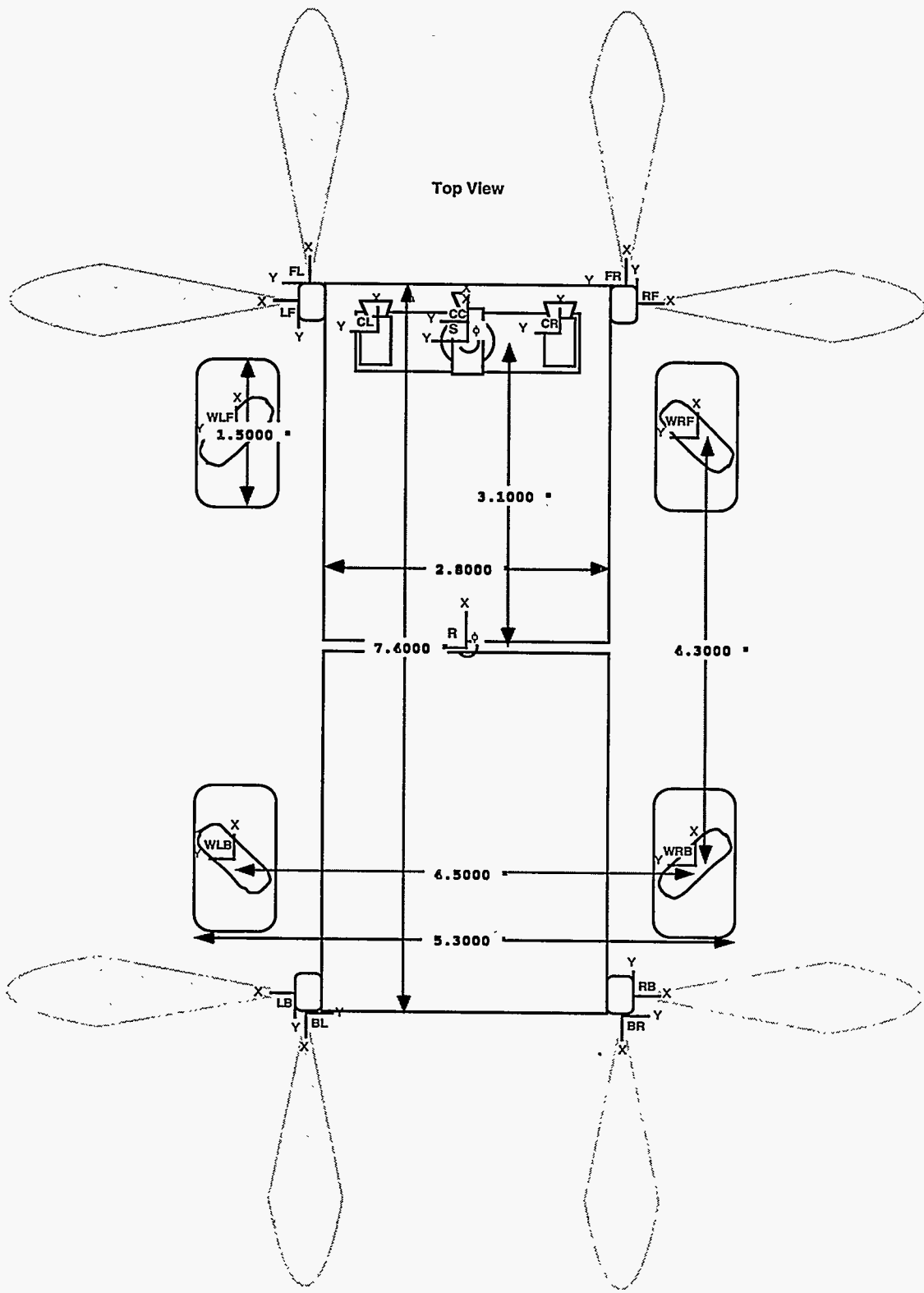
Top View

Figure 5-23. IMSS Phase 1 Vehicle Coordinate Frames.

5.3.5 Navigation Subsystem

The navigation subsystem uses two general methods of navigation: dead reckoning and feature-based navigation. Dead reckoning relies only on wheel odometry while the latter uses various sets of sonar ranging sensors to guide the vehicle relative to known features in the facility such as rows, aisles, and other landmarks.

5.3.5.1 Dead Reckoning

Dead reckoning errors are a function of such factors as wheel controller velocity following accuracy, vehicle and kinematic parameter uncertainty, and wheel slippage. To minimize the effects of odometry errors, the more reliable feature-based approach is employed whenever possible and dead reckoning maneuvers are limited to short moves for departing from the docking station and when turning to enter or exit an aisle. Furthermore, the accumulation of odometry errors are further reduced by performing frequent updates of the vehicle's world coordinates based on sonar readings against known features in the facility. For Phase 2, landmark updates were performed using the known location of pallets at the end of each row, which are stored a priori in the internal facility map.

Wheel odometry is the simplest form of navigation, also known as dead reckoning. The IMSS vehicle has omnidirectional 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 modeling errors (*e.g.,* wheel diameter) and wheel slippage on the floor. These are compensated for using feature-based navigation.

5.3.5.2 Navigating Aisles

Navigating within an aisle (the space alongside a row of drums) is feature-based and involves two concepts: "drum finding" and "aisle following." Basically, the method is as follows:

From the vehicle's current location within an aisle, move forward (or backwards) at a constant velocity and count a specified number of drums. At the targeted drum, decelerate such that the sensor mast is lined up with the drum stack's center line (±2.5 cm) to ensure optimal placement of the sensor suites. Moreover, while navigating down an aisle, have the vehicle follow the aisle boundary formed by the floor-level pallets (*i.e.,* maintain a constant, safe distance along the side of the vehicle and the pallets which form the row containing the target drum stack).

Drum finding employs the mast-mounted ultrasonic transducers (see Figure 5-24). Using the mast's leading sensor, the drum surfaces are mapped with respect to vehicle position. A drum's center line is determined by analyzing the computed slope of the mapped surface. Aisle following uses two sonar sensors mounted on the side, fore and aft, at the pallet level (Figure 5-25). Each channel of sonar data is digitally filtered to reject spurious points (spikes and acoustic cross-talk between sensors), and to smooth the discretized data prior to numerical differentiation. Moreover, to avoid injecting an external disturbance mapping the drum surface, vehicle corrections for aisle following are only performed at opportune moments, such as the period of time just after a drum center has been found and before it is time to begin searching for the next drum.
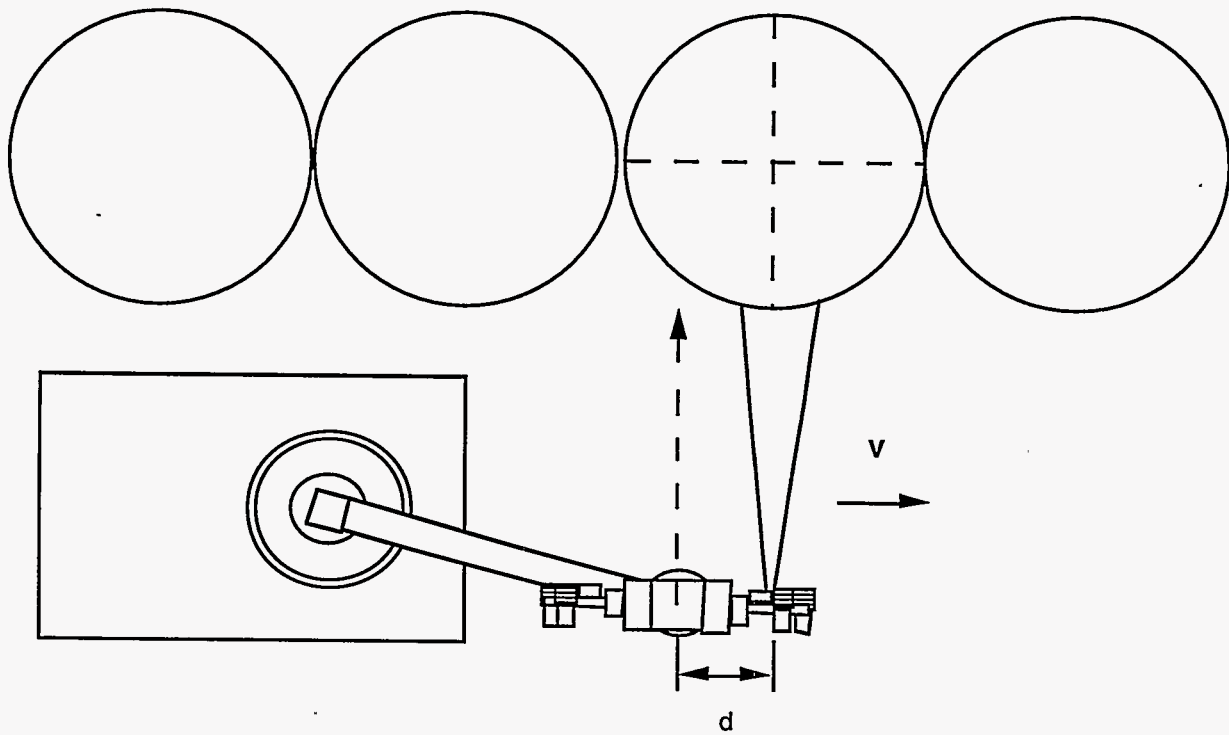
Figure 5-24. Use of Mast-Mounted Sonar to Locate Drum Centers During Aisle Following.

12 degree field of view
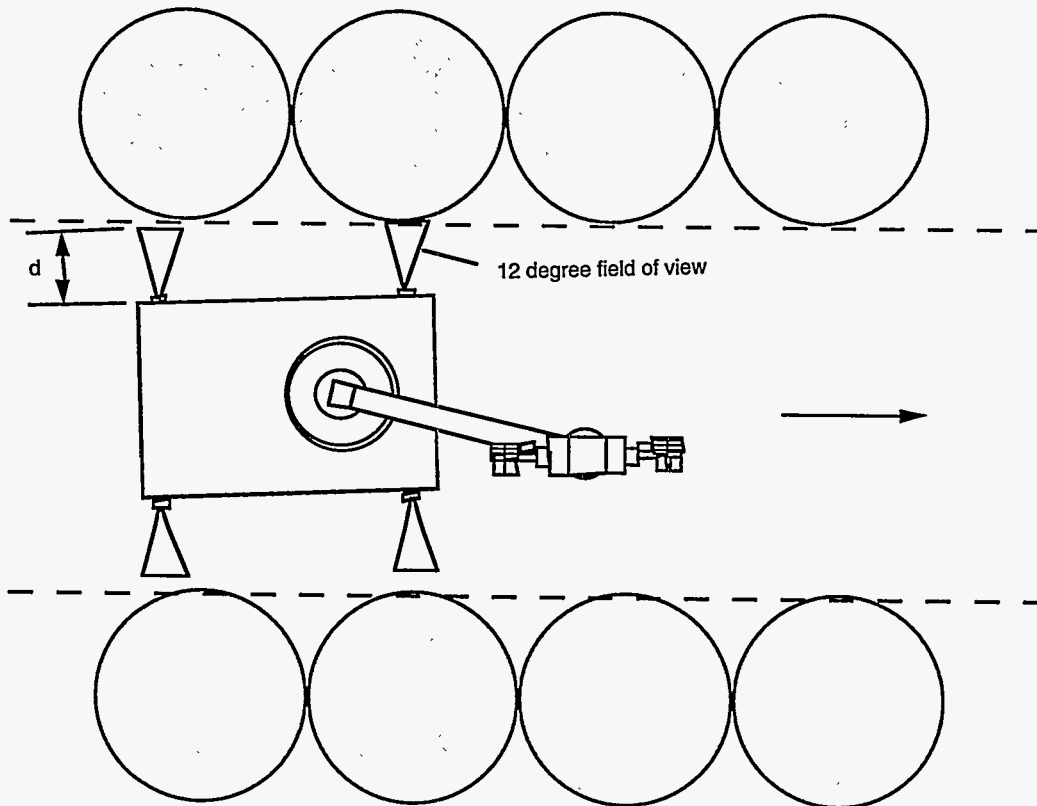
Figure 5-25. Use of Lower Side-Mounted Sonar to Follow Side of Aisle.

5.3.5.3 Finding Aisles

Aisle finding is one of the feature-based navigation modes and is used when navigating along the "corridor" for a group of rows, where "corridor" is defined as the open space along the end of rows. It is a logical feature of the facility map. The vehicle can only enter (exit) and aisle from (to) a corridor. Aisle-finding mode begins when the vehicle has entered a corridor's "access point" by way of a dead reckoning maneuver from, say, the docking station. Upon entering the corridor, the vehicle uses side-looking ultrasonic ranging sensors mounted at the pallet-level to "find" the edges of a pallet while traveling forward (pure Cartesian x translation) at a constant velocity. Each pallet defines a row. Hence, in order to navigate to a designated row, the mission executive (having full knowledge of the number of rows between the vehicle's current location and its target destination) specifies the count of rows to find along the current corridor. To reduce the effect of odometry errors, each time a row was found, the pallet sonar sensors were used to "square" the vehicle with the pallet and to maintain a constant distance between the vehicle and the end pallet (similar to the aisle following scheme described above). This correction assures that the vehicle does not stray off course of the desired forward heading.

5.3.5.4 Obstacle Avoidance

The obstacle avoidance mechanism is coupled with any motion of the mobility platform and is based on proximity detection using 16 ultrasonic transducers (arranged 4 per side), as shown in Figure 5-26. Sonar range data is sampled at 5 Hz, digitally filtered (for spike rejection and smoothing) and the following criterion applied: if three consecutive range samples are less than a given threshold, signal the presence of an object and stop the vehicle immediately, aborting the current move in progress. Selection of the set of sonar sensors is a function of the direction of travel and the mode of navigation. The proximity thresholds, also mode dependent, are used to limit the sensor's field of view, and hence control the degree of coverage. For instance, for free-space maneuvers (dead reckoning mode) all of the sensors are used to provide maximum coverage around the vehicle's perimeter. However, while moving backwards down an aisle (aisle navigation mode), only the rear-looking sensors and the side-looking sensors opposite the row being followed are used. Due to the tight confines of an aisle, proximity thresholds are reduced to avoid signaling the drums as false obstacles.
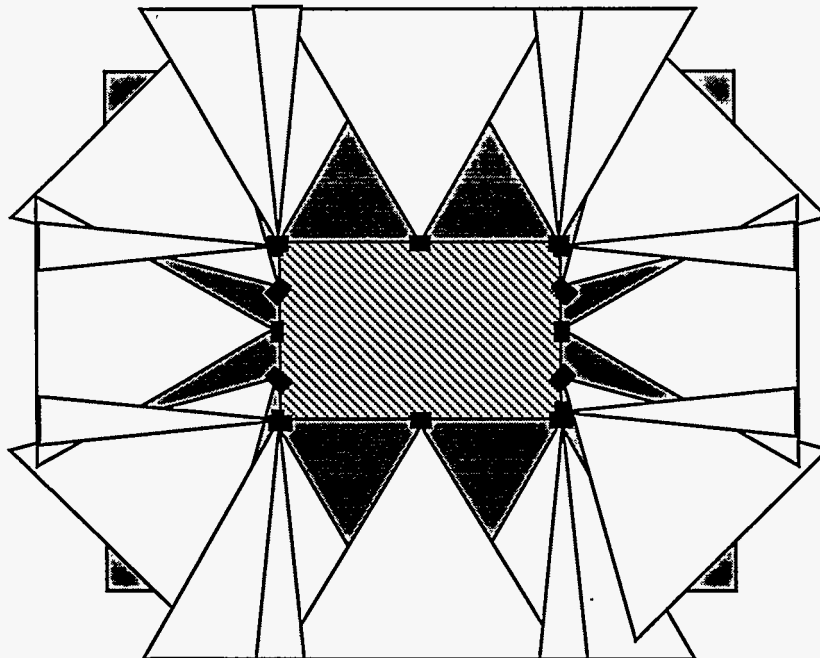
Figure 5-26. Coverage of Obstacle Avoidance Sonar Sensors.

Upon detecting an obstacle, no attempt was made to automatically alter the current path to negotiate around the obstacle. Instead, the error condition and subsequent control was passed to the real-time planner for a decision on how to recover. For Phase 2, the only recovery plan implemented was in the case of a blocked aisle. Namely, abort any further inspection of the current aisle, and back out, inspecting as much of the neighboring row as possible (assuming it is part of the mission assignment). This is a sufficient response, considering that the aisle widths are too narrow to negotiate an obstacle. However, in the case of a detected obstacle elsewhere, the vehicle would essentially abort the remainder of the mission assignment and return to the docking station, provided there was enough clearance to turn the vehicle around. In general, this is not deemed sufficient and more intelligent handling of non-aisle obstacles will need to be implemented during Phase 3. Moreover, while the current layout of ultrasonic sensors provides sufficient detection of obstacles around the sides of the mobility base, it does not provide sufficient coverage for the sensor mast, especially with regard to the detection of interfering overhangs. Additional sensors need to be integrated along the sensor mast to provide a more extensive envelope of protection.

5.3.6 Mission Sensing Subsystems

5.3.6.1 Geometric Inspection System

The geometric inspection system is a modified design with new algorithm implementations, based on the similar system initially developed for the Phase 1 vehicle. For context, an updated version of portions of the original design discussion is incorporated here from the Phase 1 report.

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.

5.3.6.1.1 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 Perceptron. The advantages of structured light systems are low cost and accuracy. Disadvantages include the time required to scan the scene and the limited depth of field.

5.3.6.1.2 Overview of Design

Structured light was selected as the range sensing technique for the task of drum surface inspection. This selection was driven by the 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, a black and white CCD camera, and image processing algorithms. The laser and camera are mounted on a tilt mechanism to allow scanning of the entire scene, as shown in Figure 5-27 and Figure 5-28. The sensors are positioned vertically on the mast so they are approximately opposite the mid-level of each drum. Each sensor suite tilts to scan it's laser line from the bottom to the top of a drum. The configuration permits full vertical measurement of both 55 and 85 gallon drums. All algorithms are implemented on the C40 DSP processors. There are three major steps in the algorithm (grab an image, find the light stripe in the image, compute 3D points on the light stripe), which must be repeated for each of the 175 images taken of each drum. The first two steps are performed in real time (for all three sensor suites in parallel), so the grabbed images need not be saved.
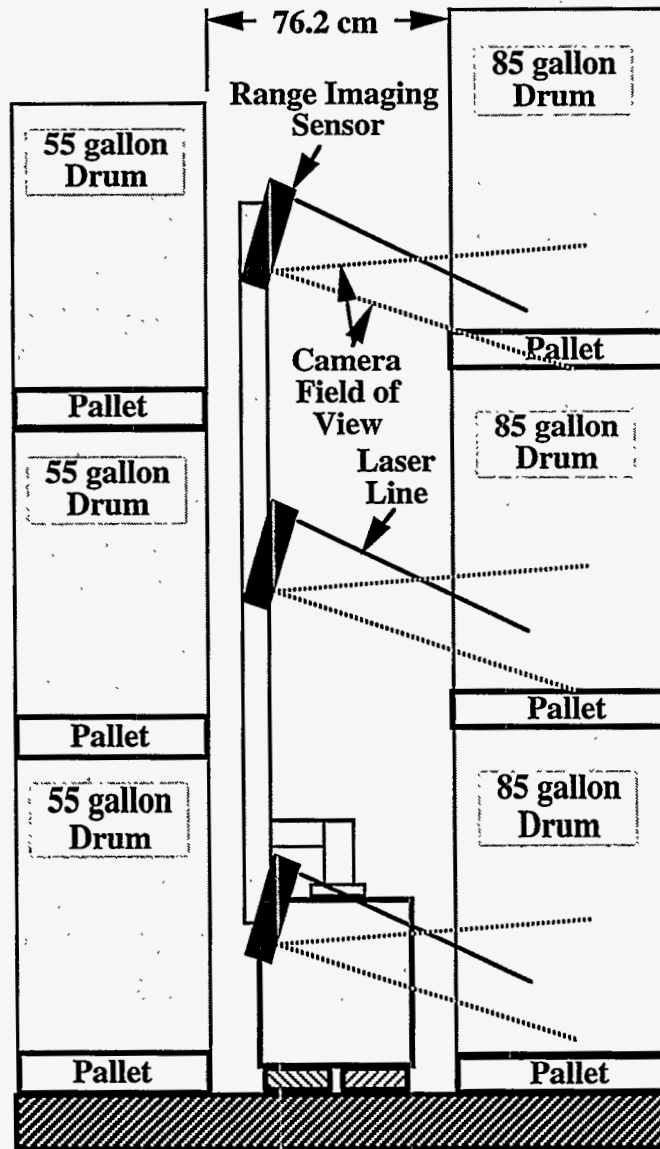
Figure 5-27. Geometric Inspection System Overview.
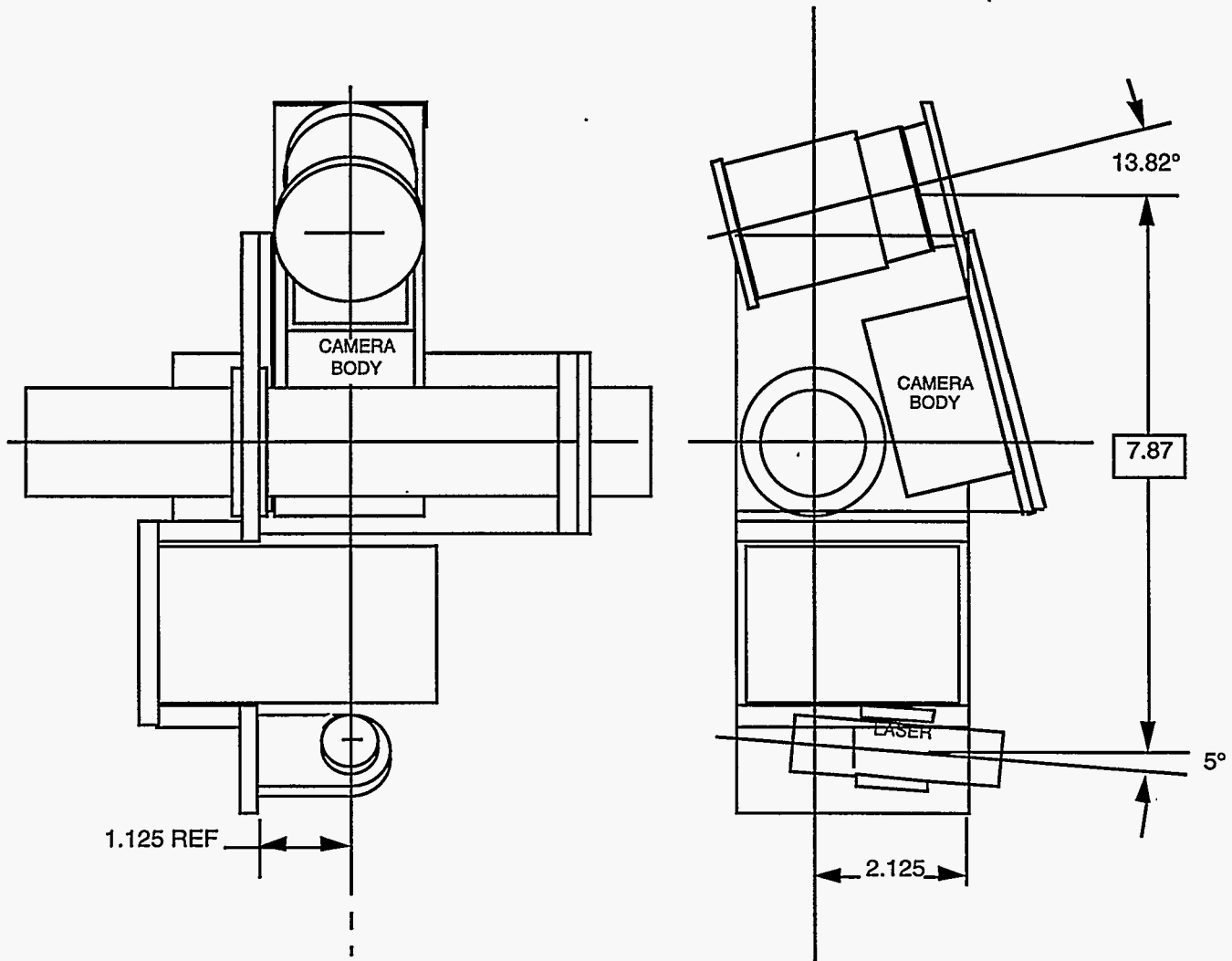
Figure 5-28.   Geometric Inspection System Sensor Suite Detail.

The 30 mW solid state laser is Class IIIb (moderate risk). However, the intensity of the light stripe a couple feet away is less than 1 mW over a standard 7 mm aperture because of the beam spreader, which is permanently attached. This brings the classification down to Class II (low risk). The wavelength of the laser is 690 nm. Long pass filters with a cutoff wavelength of 665 nm are mounted in front of the cameras to eliminate most of the background light. Short pass filters with 750 nm cutoff are also used.

Figure 1-4 showed an example of the set of 3D points measured by the system for one drum.

Features of the new geometric inspection system designed for Phase 2 include:
- All processing moved on board the vehicle (C40 DSPs).
- Improved accuracy.
- Detection of smaller dents.
- Increased inspection rate (up to four drums per stack).

5.3.6.1.3 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, the imaging system must be calibrated with respect to the vehicle. There are 4 steps involved in this calibration procedure:

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 tilt axis. This allows 3D points which have been located with respect to the laser system, to be determined with respect to the sensor suite.
3) Calibration of the zero point and the scale of the tilt axis. This allows 3D points which have been located with respect to the sensor suite to be determined with respect to a fixed coordinate system coincident with the mast. 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 mast coordinate system with respect to the vehicle coordinate system. This is determined by manual measurement.

Automatic procedures have been developed 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 tilt axis 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). The procedure uses 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 the camera with respect to the laser, a virtual target model is created using the Y-Z lookup tables. From these lookup tables, a set of (X, Y, Z) points is extracted as well as their (x, y) image locations. 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.

Next the location and orientation of the tilt axis with respect to the cameras is determined. This is done by observing a target at one position, determining its pose with respect to the cameras, moving the tilt, and observing the target again from the new position. From the two computed poses to the same target, how the cameras moved from one position to the next can be estimated. In this manner, the pan and tilt axes are found with respect to the cameras.

5.3.6.1.4 Algorithm description: locating drums

During operation, when the system inspects a drum, it must first determine the drum's location. There are two reasons for this: (1) the precise location of the drum is unknown, and (2) it must be determined whether the drum is tipped (which could indicate bulging of the ends). The 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, the drum finding problem is much simpler because the drums have such a simple geometric model. It is sufficient to model the drums as cylinders of a constant known diameter. Ribs, dents, and rims show up as small geometric deviations from the model. A simple algorithm was developed 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. Pairs of points are taken at random from the image. For each pair, the direction of the cross product of their surface normals is computed. 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, it is known which points in the range image are likely to lie on the drum. Since the radius of the drum is known, it is known 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, a ray is projected inwards along the surface normal to a distance equal to the drum radius. A line is then projected along the drum axis downwards until it intersects the floor. By clustering these intersection points, the intersection point of the drum axis with the floor can be determined.

This procedure is tolerant of some occlusion of the drum surface, the presence of background objects, and the presence of dents and ribs.

5.3.6.1.5 Algorithm description: locating dents

Once a range image has been taken and the drum located within the image, the next task is to detect any dents in the drum. Dents are defined to be deviations from the nominal drum surface beyond a threshold in vertical depth and having a lateral area beyond a threshold value of square centimeters. The 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. Ribs are excluded 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.

5.3.6.2 Color Vision System

The color vision system (COR) subsystem detects visual anomalies (rust, streaks and corrosion) on each drum in a stack using two color cameras in the sensor suite opposite each stack level. The two cameras provide views of the visible left and right sides of each drum. The color camera is a Pulnix TMC-7 using a single CCD element. An 8 mm lens is used, based on comparing various lenses for the drum inspection requirements. Four to six images per drum are needed for medium resolution inspection (locating pea-sized rust spots) for 55 and 85 gallon drums respectively. Adjacent to each camera is a compact 20W video (halogen) lamp which is turned on only during image acquisition. The lamp helps provide more uniform and controlled illumination of the drum surface in typical waste storage facilities, which may have highly variable lighting conditions. During inspection the cameras are nominally positioned about 45 cm from the drum. Vision software runs under control of the system executive, and as soon as the current set of images is digitized, the tilt units and vehicle are released to perform other tasks while the images are processed. All image processing runs on C40 DSP processors. The part of COR that runs on the vehicle's host processor performs only executive types of functions and also interfaces with the defect database.

Image analysis algorithms were developed on a UNIX workstation using the Khoros image processing package. Optimized versions of the image processing software run directly on the C40/framegrabber boards instead of on a workstation. The drum color is first determined, and then separate modules (with color-dependent parameters) identify rust, streaks and corrosion.

Drum color. Drum color is determined by a nearest neighbor classifier using average RGB values from centered subimages. If the detected color is different than the expected color (available from the world model during normal inspection operations) then the new-defect database is notified.

Rust detection. Two rust detection algorithms were developed and studied. Both start with a smoothing filter on the input RGB image to eliminate noise and reduce sharp edges.

    Color thresholding. The RGB images are transformed into the Ohta color space [Ohta *et al.* 1980]. The new image bands are "intensity" = $(r + g + b)/3$, "red - blue difference" = $r - b$, and "excess green" = $(2g - r - b)/2$. Various thresholds are applied to these bands, producing binary images that are then combined. Rust and labels are detected independently, then rust-like things detected inside label areas are ignored. This is necessary since some labels contain red, rust-colored, markings. A binary image showing all pixels classified as rust is created.

    Nearest neighbor classifier. Each pixel in the image is classified as rust or the (previously classified) drum color using a nearest neighbor classification algorithms using RGB values. A binary image showing all pixels classified as rust is created.

The resulting binary image showing rust pixels and areas is cleaned up using morphological operations, and binary blob analysis algorithms provide features for each rust spot (*e.g.,* spot height, width, area).

Streak detection. Streak detection is run as a post-processing step to 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). Morphological shape filters are iteratively applied to identify extended streaks in the binary images produced by the rust detection algorithms.

Several other potential inspection algorithms were considered or examined during Phase 2, including: microfeatures such as statistics (mean and standard deviation) and texture (entropy and homogeneity) on small windows (5x5), macrofeatures such as variance and Singular Value Decomposition eigenvalues [Pratt 1991] on larger windows (15x15) from the textured images, and two supervised clustering methods for pattern recognition: a conventional k-means algorithm [Coleman and Andrews 1979], and the Learning Vector Quantization neural network algorithm [Visa 1990].

5.3.6.3 Bar Code Scanner

Bar code labels are used to identify and track waste storage drums. For autonomous label scanning two Symbol Technologies Laserscan 6120 visible laser diode scanners with four scanner heads are used (three scanner heads are used, the fourth is for the optional mast extension). This laser operates at 680 nm with 1.0 mW maximum 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 the vehicle's host computer. The scanner heads are mounted on each sensor suite's tilt axis, so they can read a barcode label located anywhere vertically on a drum that is within 60 degrees of the drum's face. DOE facilities normally place the bar code in the center third vertically and centered horizontally. 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.

Bar code labels are similar to those examples provided or described by different DOE sites (1" tall vertical bars, medium density, Code 3 of 9 symbols, with 10 alpha-numeric characters, mounted with code bars vertical).

5.3.7 Operator Interface

During an inspection mission, all vehicle activity is coordinated by the on-board mission executive software and its real-time planner. However, site personnel are involved to supervise operations before and after a mission. This is done through a graphical user interface from a remote operator control station. During Phase 2, a full-scale operator interface was developed that provides key interfaces such as *Facility Model Creation/Editing, Mission Assignment, Mission Assessment*, and *Report Generation*. Each of these functions is described in a section below. First however, some background information of facility models is provided.

5.3.7.1 Facility Model

A model of each facility must exist before an operator can assign inspection missions inside it. The facility model is normally created by the system administrator. The inspector/operator normally does everything else.

The facility model is actually a set of databases containing three kinds of information:

Facility map. The facility map is a description of the physical layout of the facility, meaning such things as the number, size and location of aisles, pallets, ramps, obstacles, *etc.* This information is entered using the facility model editor function in the operator interface.

Drum database. The drum database contains an entry for each drum in the facility, and contains information such as drum barcode, size, color, location. Some of this information is provided from the physical layout of the facility. Any missing information is obtained during the initial "baseline" run that the vehicle makes through the facility. Drum and some facility information may be provided by existing external facility databases, in which case the baseline run serves to verify and update that information.

Defect database. The defect database contains all defect-related information from the inspection process. Defects are indexed by the corresponding facility model drum id, usually the drum's barcode. A master copy of the defect database is maintained inside the operator console. Before each inspection mission, a copy of this database is provided to the vehicle for reference during the mission (*e.g.,* so previously detected defects that were identified as acceptable by a human operator are not reported again). A database of new defects is created during the inspection mission. After the mission, the operator reviews these new defects, identifies those that are acceptable defects, and the results are merged into the master copy of the defect database. The defect database also contains pointers to separate image files showing each defect.

There is one facility model database for each waste storage facility.

Note that another purpose of the baseline run is to automatically detect all acceptable defects in the facility. It is assumed that a human inspector has examined the facility before the baseline run and that no unacceptable defects exist in it. Thus all the defects detected by the system during the baseline run are automatically known to be acceptable ones.

5.3.7.2 Facility Model Editor

The operator uses the facility model editor to create an overhead plan view of each facility, drawn to scale. Initially the display screen shows a blank overhead view. The interface is similar to that in a drawing program. The user can select, draw, place, move, and re-size primitive facility objects (*e.g.,* aisles, pallets, obstacles, the docking station) anywhere in the overhead map view of the facility. Figure 5-29 shows the screen for the facility model editor. Once the facility map is complete, the user saves it to a file, which is called the facility model map. Figure 5-30 shows a labeled example of such a map, and Figure 5-31 shows a map for a large facility.

XFIG 2.1 patchlevel 8 (Protocol 2.1)

| Quit | Delete ALL | Undo | Redraw | Paste | File... | Export... | Print... | Mouse Buttons |

sample1.fig | PATH drawing: define a vehicle PATH

Drawing modes

Facil	Area
Corr	Row
Way	Pose
Path	Obst
Lmark	

T

Editing modes

Scale	Align
Move	
	Copy
	Delete
Update	Edit
Rotate	Rotate

1 2 3 4 5 6 7 8 9 10 in

Hanford WSF 2402 Series: 80' x 50' (# of 55-gal drums: 836)

Ramp

Ramp

N

| Zoom Scale 1 | Grid Mode NONE | Point Posn | Depth 1 | Angle Geom | Fill Style NONE | Color Black | Line Width | Line Style | Arrow Mode |

Figure 5-29. Facility Model Editor.
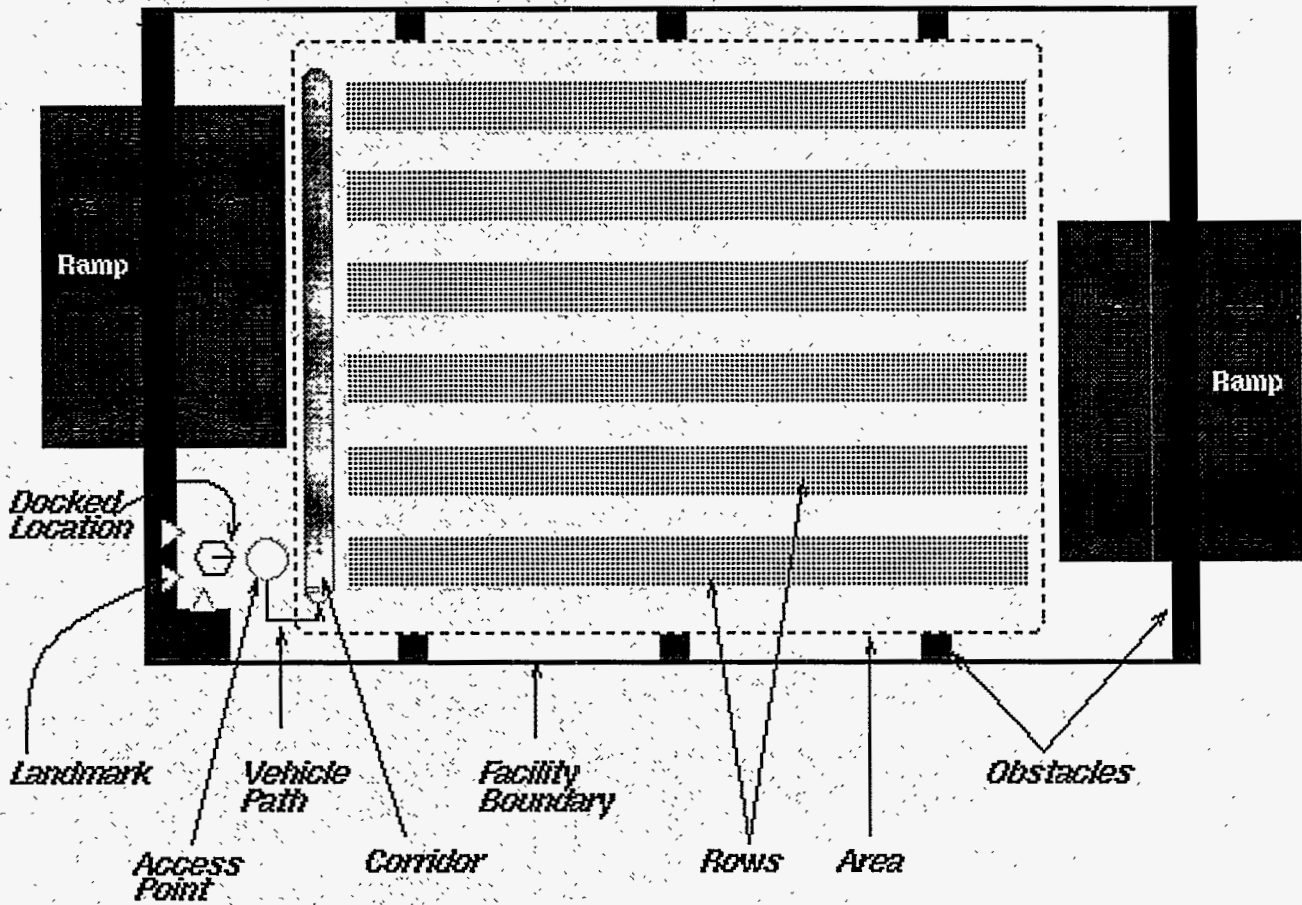
Figure 5-30. Labeled Example of a Facility Model Map.

Figure 5-31. Example of a Large Facility Model Map: Hanford WSF 2403 Series.

Hanford WSF 2403 Series: 200' x 170' (Tot # of 55-gal drums as shown = 9924)

Ramp

Ramp

N

5.3.7.3 Mission Assignment

Mission Assignment allows an operator to designate the areas of a facility to be inspected, specify the exact sequence of rows, or simply confirm a default assignment based on the facility's current state of inspection. This interface generates a data file which the vehicle down-loads while docked at its charging station. After the vehicle has received its assignment and is fully charged, at an operator-specified time of day the vehicle departs, inspecting drums until the assignment is completed, or a low state-of-charge condition is signaled. After returning to the charge station, mission results are up-loaded to the control station for subsequent review.

5.3.7.4 Mission Assessment

Using the Mission Assessment interface, an operator can review a mission's defect logs, display color images of the defective drums and then generate a report summarizing the mission, along with a list of reported defects and a map of the facility specifying the location of the defective drums. Figure 1-6 showed a sample of the Mission Assessment interface.

5.3.8 Executive

The mission executive directs the integrated action of the various functions (subsystems) of the vehicle to achieve an efficient and complete inspection of the facility. The functions controlled include navigation, bar code reading, geometric inspection, and corrosion inspection. The details of how each function is performed are left to the individual subsystems. The mission executive simply issues commands (via the VxWorks message passing system) to subsystems, and checks for reports back from subsystems. 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 do not. Second, maximizing concurrency of task performance will tend to minimize inspection time.

The mission executive consists of three main parts:

Plan scheduler. The mission assignment function of the operator interface results in a complete mission inspection plan. This plan is downloaded to the vehicle, and is the input to the plan scheduler. The plan scheduler then coordinates the execution of commands, as specified in the plan.

Mission monitor. The mission monitor monitors the progress of each commanded process, watching for error codes and recording a history of the executed mission, including the vehicle path.

Contingency planner. The contingency planner is invoked when the mission monitor detects special mission-specific error codes (*e.g.,* blocked aisle, low-power condition, sensor failure). It generates a contingency plan of action to salvage as much of the intended mission as is possible. At worst, it will send the vehicle back to the docking station.

5.4 Test Facility

5.4.1 Waste Storage Facility Mockup

A new waste storage facility mockup was created at Lockheed Martin's Denver location during Phase 2. The test facility used during Phase 1 is located in a truckwell area adjacent to the new facility, and has received occasional use.

The Phase 1 facility, located in the truckwell, is diagrammed in Figure 5-32. 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 is 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. This test area is in the lower end of the brightness scale providing a worst case environment for development. The test area was 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, and were secured to the wall for safety. The center row was one stack high. Since the truckwell was active during the testing phase and trucks and equipment had to move through the area, the center row of drums 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.
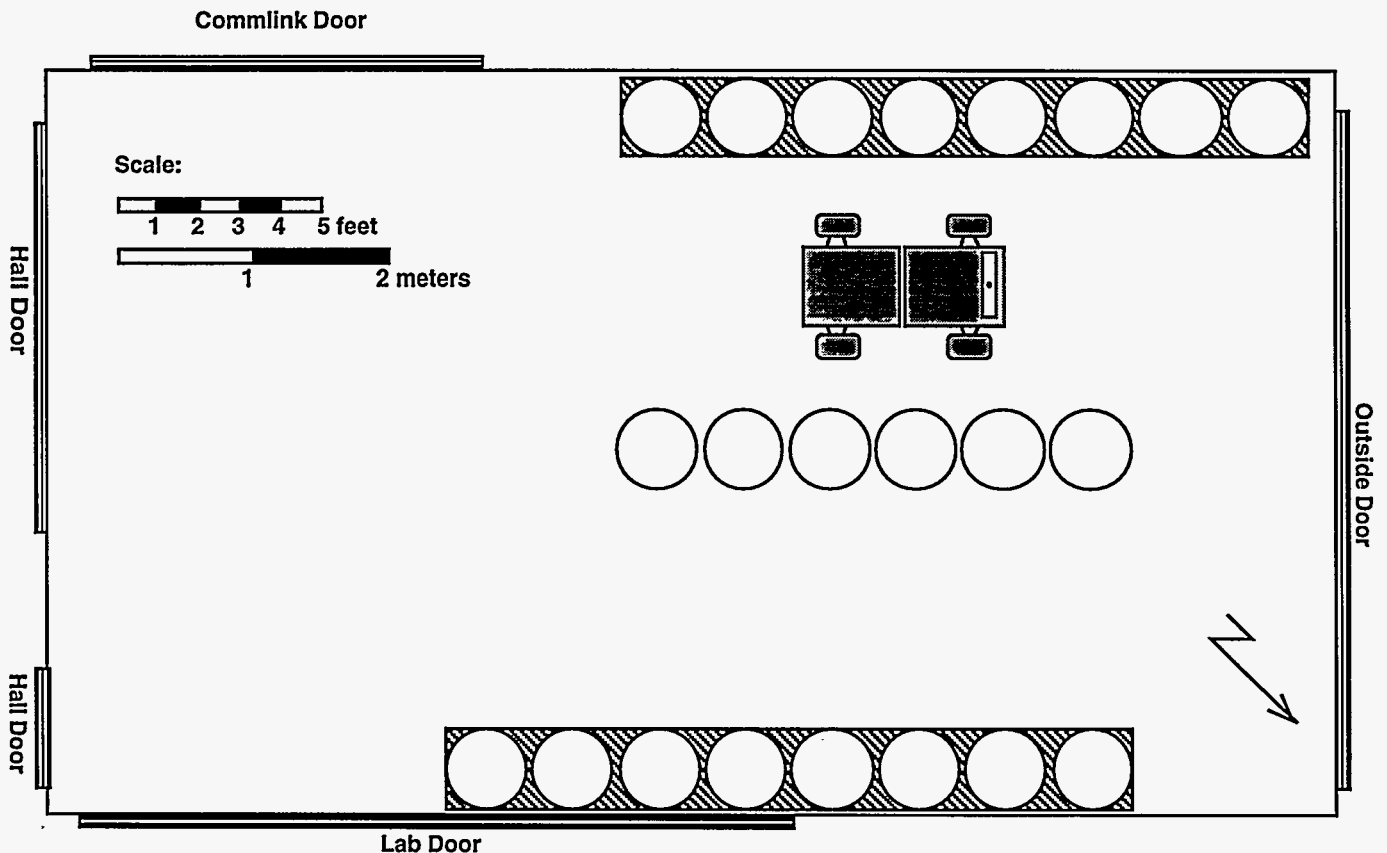
Figure 5-32. Diagram of Phase 1 Test Facility.

The new Phase 2 mock facility is shown in Figure 5-33. This facility is configured in a laboratory approximately 24' x 30' x 15' high. It contains a staging area (simulating the location of a battery charging station) and three rows of banded and palletized 55-gal. drums (4 per pallet) stacked from two to three levels high. Each row is four pallets deep (12'); however, an overhang at one end was too low to clear the sensor mast, inhibiting navigation to the last stack in each row. Hence, the rows are effectively "dead-end" in that the vehicle can only enter an aisle from the open end, backing out in order to exit. The final test configuration contained 80 inspectable drums. The aisle widths (space between adjacent rows) are 36 in. wide. Some known obstacles are present, such as the overhang, and work desks. The floor surface consists of smooth linoleum tiling over a concrete foundation. The operator's control station was located in a room adjacent to the storage area, just on the other side of the wall by the staging area.
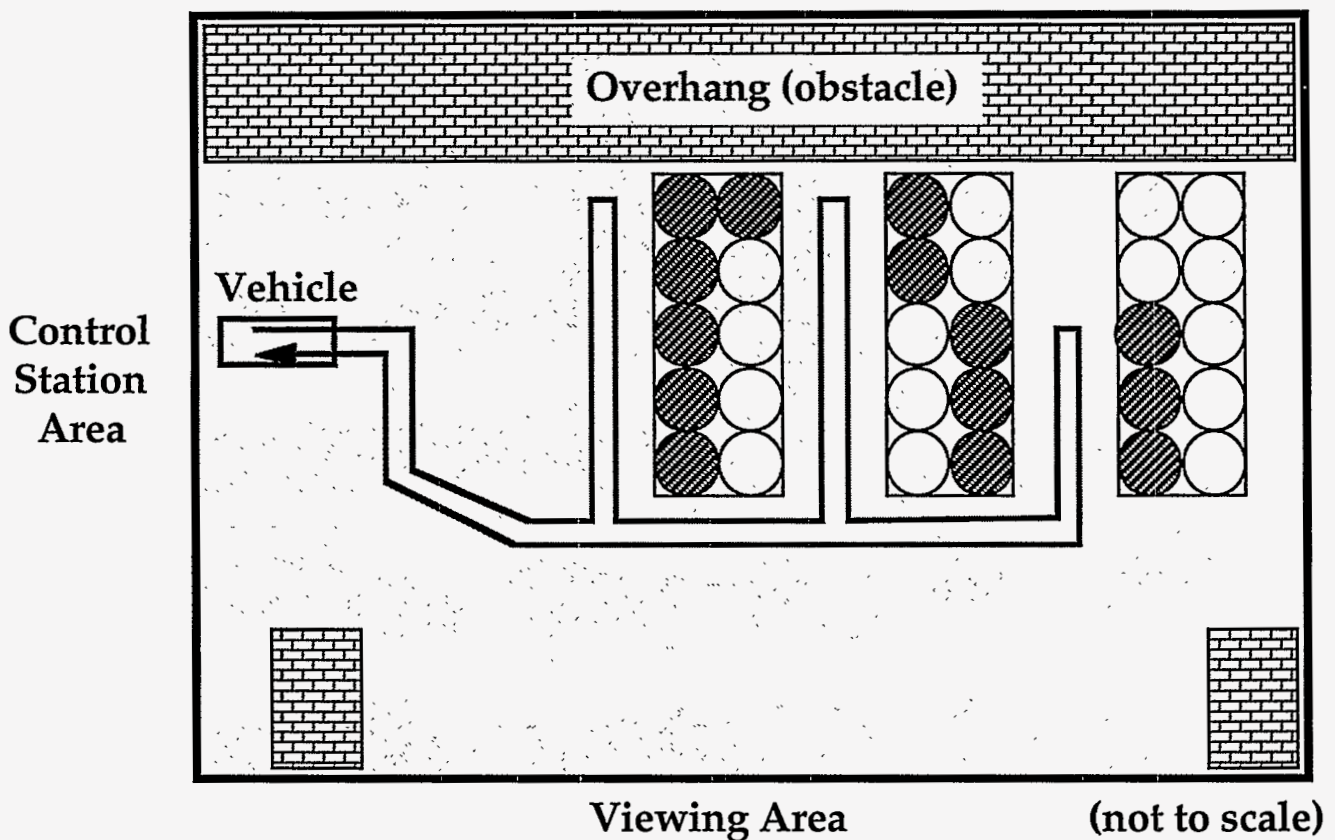
Figure 5-33. Diagram of Phase 2 Mock Storage Facility.

5.4.2 Preparation of Drums for Mock Facility

New waste drums that had not been used before were installed in the test facility. New drums were required 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. Approximately 84 drums were located in the facility including 55 gallon and 85 gallon sizes. Colors included black, yellow, white, mauve (purple), silver (stainless steel), and shiny silver (galvanized steel). Drum 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.

Several 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 drums. These bare metal patches were then repeatedly sprayed with salt water over the course of several weeks. Rust patch size varied from large 30 cm^2 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 drums with methods ranging from using a hammer to using a very large rock. Dent depths ranged from 1 cm to 8 cm.

All drums were marked with a barcode. These conformed to current DOE specifications obtained form some sample barcodes. The barcodes were 2 cm x 5 cm and followed code 39 specifications. The labels were oriented with the bars in the vertical direction ("picket fence"). A barcode numbering scheme was implemented and tied into the mock facility's site database and reporting database. Each barcode was located in the upper third of the drum and was oriented to approximately face outward. Barcode defects were added to many drums. Barcode defects included placing the barcode in the middle and bottom thirds of various drums, some labels were placed off-centerline anywhere on the front quarter of the drum, and many barcodes were torn and/or scuffed.

6. RESULTS AND DISCUSSION

This section presents the result of Phase 2 evaluations, including basic testing and performance evaluations. For Phase 1 results using the Phase 1 vehicle, the reader should consult the IMSS Phase 1 Topical (Final) Report [IMSS Phase 1].

6.1 Subsystem Evaluations and Performance

6.1.1 Mechanical Subsystems

6.1.1.1 Vehicle Structure

The vehicle structure has proven to be exceptional. The vehicle frame and frame/mast combination met all stiffness requirements. No torsional flexibility was observed about the roll axis. Mast vibrations are greater than one hertz and damp out within three seconds. Tipover angles were verified in both longitudinal and transverse directions with the mast in the worst case position for both cases. The specification was exceeded (17 and 19 degrees respectively (equivalent to driving over a 2x4)).

6.1.1.2 Motion Platform

The mechanical elements of the vehicle motion platform proved more than satisfactory during the Phase 2 evaluation period and demonstration. The twenty inch width gives adequate clearance within aisles. Minimal vibration is injected into the platform by the wheels. Access for repair is more than adequate. The wheel drive motors can even be changed out in place although a modified wrench is required. Mounting the mast is very simple: there are eight bolts on the base structure, and a number of connectors on the electrical interface panel.

6.1.1.3 Sensor Mast and Sensor Suites

The mechanical elements of the sensor mast and three sensor suites proved more than satisfactory during the Phase 2 evaluation period and demonstration.

Image acquisition of drum faces covers 100% of the viewable area. All levels and all sides of all drums on both sides of all aisles can be viewed by the sensor pointing system. No exceptions are made for deadend aisles or non-homogenous stacks.

The vehicle design includes an optional mast extension, which extends the inspection capability from 3-high to 4-high stacks. This mast was not manufactured due to cost constraints, but several DOE facilities have 4-high stacks and would need it. All sensor pods are similar and can be easily removed and/or interchanged.

6.1.2 Electrical Subsystems

6.1.2.1 Vehicle Electronics

The vehicle electronics (host computer, Galil motion control boards, C40 boards, *etc.*) have performed adequately. The Galil boards are known to have rather tight operating requirements, which can occasionally cause problems. One such problem was encountered during Phase 2 vehicle integration: anomalous behavior occurred when the 5V supply voltage to the boards was only slightly below 5V. This problem was fixed by improving the current carrying capacity of the 5V feeder cables, which had caused the voltage to drop very slightly. Exception handling of other hardware faults is driven by the

executive such that individual subsystem error conditions can be hard reset by the executive software. This capability was validated and demonstrated.

The electrical and electronics subsystems were designed to accommodate the addition of future elements into the vehicle. Integration of the Lockheed Martin Palo Alto group's ABCD system is one example, which we believe should be possible (the ABCD system is still evolving, as are it's exact mechanical, electrical, and software specifications).

Performance of the hard drive has met our environmental conditions in terms of vibration, temperature, and data transfer rates.

6.1.2.2 Ultrasonic Transducers

The ultrasonic sensors provide adequate coverage for the collision avoidance system.

The bottom-side mounted sensors used to sense the sides of pallets are adequate for all but 26" aisles, which do not provide the minimum offset distance required for these sensors to work. Use in 26" aisles will require mounting of transducers recessed a few inches, a modification that can easily be accommodated in the current vehicle design.

6.1.2.3 Communications

The radio ethernet has proved adequate during testing in the Phase 2 mock facility. Because the radiolink is designed to be used only when the vehicle is docked (to avoid having to make a hard connection), noise has not been a problem and data transfer rates are high.

The radio ethernet was designed to mount on the optional docking station, which was not constructed in Phase 2. This is however a simple mechanical mount and lack of the docking station has no significance on the communication system.

6.1.2.4 Power

The power system has performed adequately under all load conditions. Heat generation is not significant. Power supply noise is not measurable, even under the hardest switching conditions (drive motors with lights, etc.). Power consumption is less than originally calculated. Although the runtime duration numbers have not been updated, they have been shown to be conservative.

Charging the battery power system to full capacity requires a high-current power supply, which was not available during Phase 2. NiCad batteries exhibit a charging behavior "memory", and not changing these batteries to full capacity is less than desirable and can reduce the useful life of the batteries. A low-current power-supply used during Phase 1 (for different batteries) was again used during Phase 2. A high-current power supply must be purchased for future work.

6.1.3 Safety System

A new and extensive safety subsystem was incorporated into the IMSS Phase 2 vehicle design. This system has proved itself on numerous occasions during the Phase 2 development period, when many hardware and software elements of the system were still being built, fixed, and debugged. As a result no significant safety related problems occurred during the entire Phase 2 effort. All of the safety system components were functionally tested to verify the proper execution of required system functions (such as software execution, response to motor commands, power state control, *etc.*); however, results from the verification tests for those components deemed most critical are presented below.

6.1.3.1 Passive and Designed-In Safety

Exposure to high battery power. Physically verified.

Structured-light sensor laser element. Physically verified. Written operating procedure in place.

6.1.3.2 Emergency System Power-Down

All causes and effects for an emergency system power-down (Table 5-2) were tested and verified to operate as designed, including the mission processor's heartbeat monitor, battery charge state, and battery over-temperature.

6.1.3.3 Emergency Actuator Disable

Each of these safety measures (Table 5-3) was tested and verified dozens of times throughout the development effort and during end-to-end operations and testing (these were mostly physical switches, software shutdown control, and servo control board errors). The contact skin has performed exceptionally well, although since the navigation and obstacle avoidance system work so well, it has been verified only by physically touching it.

6.1.4 Control

6.1.4.1 Vehicle

The onboard vehicle position control implementation has functioned satisfactorily in all testing.

An experiment was performed to measure the incremental motion control capability of the vehicle. The vehicle was commanded to perform a series of five fixed-size incremental movements in the y direction. This experiment was performed for four different fixed-size increments: 0.05 mm, 0.1 mm, 0.2 mm, and 0.5 mm. The commanded and resulting movements are illustrated in Figure 6-1.

The control system can not perform arbitrary size incremental movements. It is restricted to a limited choice of increment sizes. However, the vehicle can execute those incremental movements with extraordinary precision. The limited choice of increment size movements is a function of the motor control software.

The backlash in the wheel drive train was measured using a precision instrument that measures linear position of a built-in probe. This instrument appears to have a precision of 0.01 mm. The vehicle has pushed by hand in the +x direction to push the drive train components against one end of the backlash travel. The instrument was then positioned against the side of the vehicle, the vehicle was pushed by hand in the -x direction to the other end of the backlash travel, and the x movement measured by the instrument was recorded. This procedure was performed three times along the x axis, and three times along the y axis. The results are shown in Table 6-1.
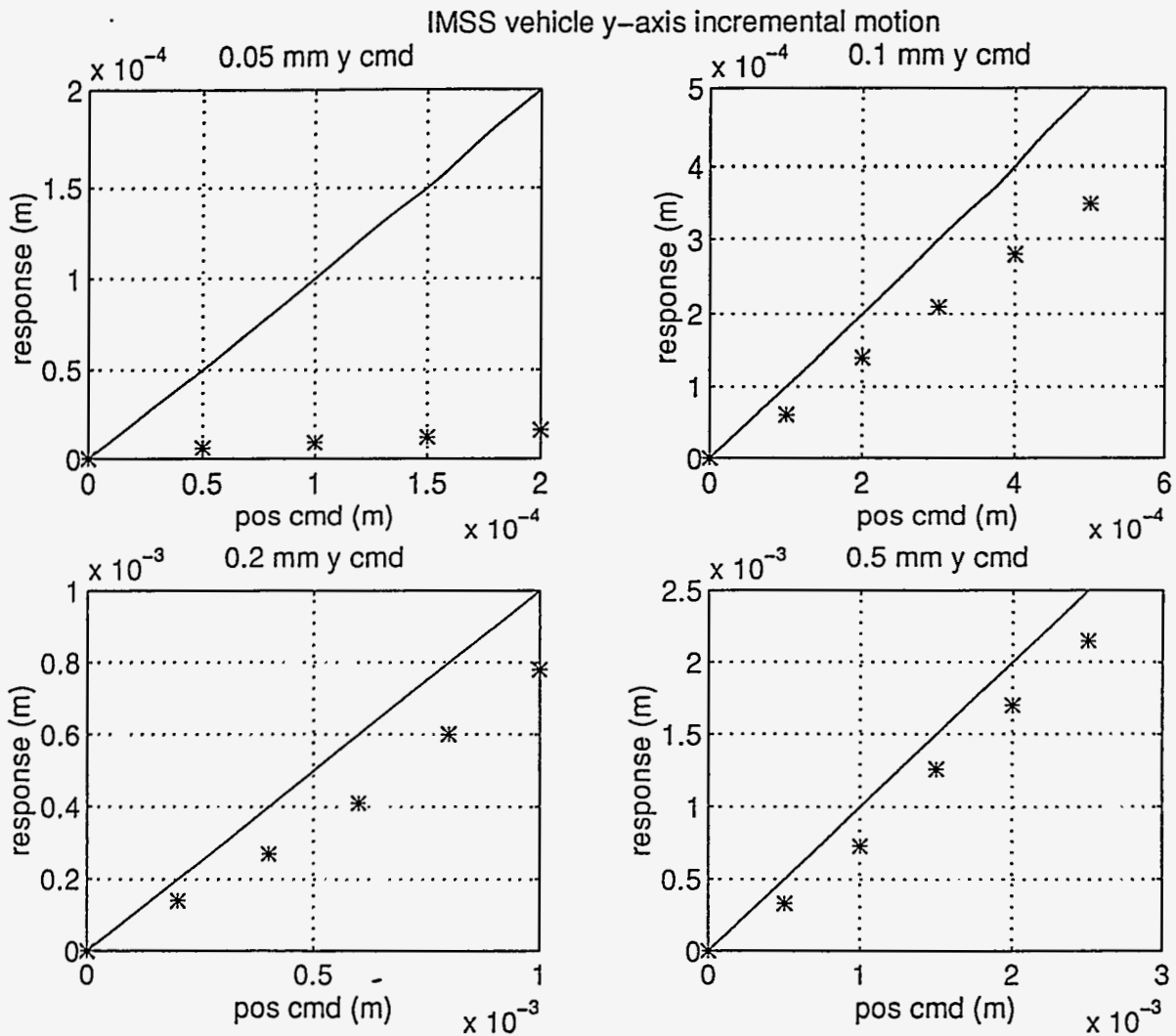
Figure 6-1. Vehicle Incremental Motion Along the y Axis.

Table 6-1. Vehicle Positioning Error Due to Wheel Drive-Train Backlash.

Trial	x-axis	y-axis
1	0.00063	0.00026
2	0.00066	0.00027
3	0.00066	0.00029

Distances Are in Meters.

6.1.4.1.1 Obstacle Avoidance Filter

The Phase 2 vehicle system nominally kept the obstacle avoidance filter turned off, since most vehicle control is now based on ultrasonic feature-based navigation. However this capability was retained since it will be useful during dead reckoning moves around the docking station and facility ramps -- situations which will exist and thus receive more attention during Phase 3.

6.1.4.2 Sensor Mast and Sensor Suites

The sensor mast control subsystem has performed exceptionally well during testing in the Phase 2 mock facility. The motion was so fine and so smooth that the GIS laser system was never affected by any noise.

6.1.5 Navigation Subsystem

The navigation subsystem functions have performed satisfactorily in all testing.

6.1.5.1 Dead Reckoning

Three experiments were performed to independently measure the repeatability in first the x direction, then the y direction, and then for phi (rotational) movements. In each experiment the vehicle was commanded in Cartesian space for a move in the (+) direction followed by an equal size move in the (-) direction.

The position of the vehicle was measured as follows: Two stiff wire-like pointer tools were mounted on the vehicle body such that the end of the pointer tool was suspended just above the floor surface. One pointer tool was mounted in the front center of the vehicle, and the other in the rear center of the vehicle. Graph paper was taped to the floor underneath these two pointer tools at each position where the vehicle would be stopping. Each time vehicle motion is commanded during an experiment, the pointer positions are marked on the appropriate piece of graph paper. Given the pointer positions from the front and rear of the vehicle, the x, y, and phi (heading) location of the vehicle are readily calculated.

In the first experiment, the vehicle was commanded to move 0.5 meters in the -x direction, followed by a similar move in the +x direction. The starting and ending positions of the vehicle were recorded. This commanded motion was repeated 5 times. Figure 6-2 shows a reproduction of the two pointer tool positions recorded on the graph paper. This raw data is interesting because it shows the scatter pattern of positions after each movement. Table 6-2 shows the calculated vehicle center location after each movement.

The second experiment is similar, but the movement was along the y axis. Results are shown in Figure 6-3 and Table 6-3.

The third experiment is again similar, except the movement was a pure rotation of -45 degrees followed by a pure rotation of +45 degrees. The results are shown in Figure 6-4 and Table 6-4.

The repeatability along the x axis is excellent. The repeatability along the y axis is fair. While an x axis movement involves driving all four Macadam wheels in the same direction, a y axis movement involves counter-rotating the wheels in each left-right wheel pair. The servo system requires some parameter re-tuning for y axis movements. Repeatability around phi is excellent.
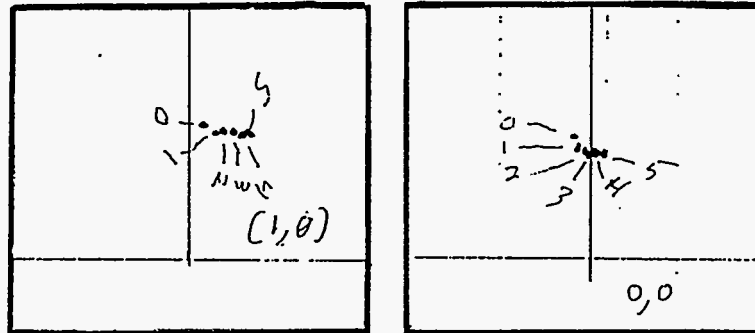
Figure 6-2. **Two Pointer Tool Positions Recorded on Graph Paper From dX.**

From the ±0.5m X Movement Experiment.

Table 6-2. **Calculated Vehicle Center Location (x, y, phi) from dX.**

movement	x	y	phi
initial position	0.5185	0.0003	-0.2524
1	0.5170	-0.0013	-0.3083
2	0.5170	-0.0020	-0.3359
3	0.5167	-0.0030	-0.3913
4	0.5165	-0.0040	-0.3911
5	0.5165	-0.0053	-0.3628

From the ±0.5m X Movement Experiment.
(x, y) are in Meters. phi is in Degrees.
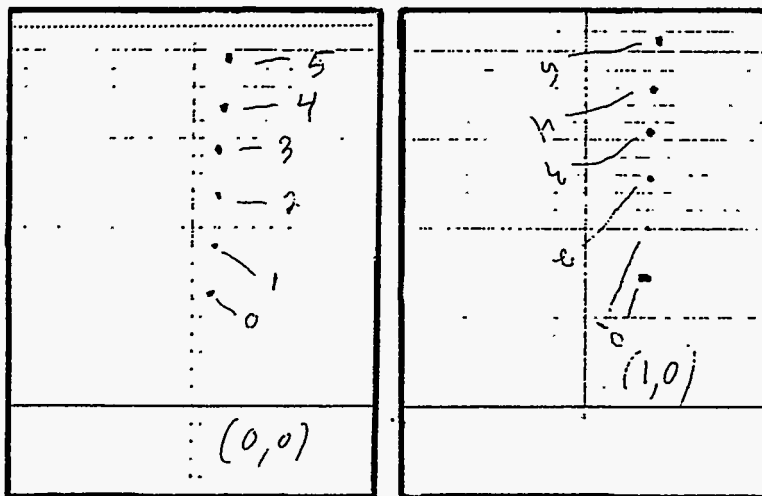
Figure 6-3. **Two Pointer Tool Positions Recorded on Graph Paper From dY.**

From the ±0.5m Y Movement Experiment.

6-6

Table 6-3. Calculated Vehicle Center Location (x, y, phi) From dY.

movement	x	y	phi
initial position	0.5172	-0.0055	-0.3347
1	0.5242	-0.0060	-0.3323
2	0.5312	-0.0065	-0.3299
3	0.5380	-0.0067	-0.3004
4	0.5443	-0.0072	-0.2986
5	0.5513	-0.0077	-0.2964

From the ±0.5m Y Movement Experiment.
(x, y) are in Meters. phi is in Degrees.
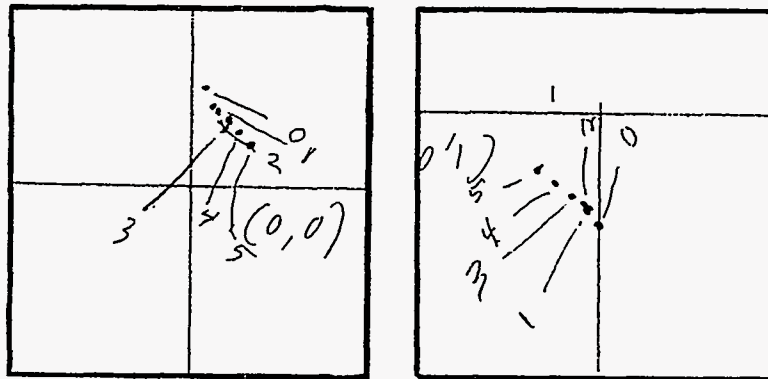
Figure 6-4. Two Pointer Tool Positions Recorded on Graph Paper From dØ.

From the ±45 Degree phi Movement Experiment.

Table 6-4. Calculated Vehicle Center Location (x, y, phi) From dØ.

movement	x	y	phi
initial position	0.5152	-0.0010	0.1128
1	0.5128	-0.0025	0.1128
2	0.5120	-0.0030	0.1129
3	0.5108	-0.0043	0.1411
4	0.5092	-0.0067	0.0282
5	0.5072	-0.0088	-0.0282

From the ±45 Degree phi Movement Experiment.
(x, y) are in Meters. phi is in Degrees.

6.1.5.2 Navigating Aisles

The aisle navigation scheme was functionally tested during the integrated, end-to-end inspection missions and also in stand-alone tests on 36" aisles. The vehicle was positioned at the entrance point of an aisle and commanded to find n stacks going forward and then return to the starting stack moving backwards. To exercise the aisle following capability, the vehicle was initially oriented such that corrections would be necessary in order to prevent eventually straying into the adjacent row of drums. At the target stack, measurements were taken to ensure the mast was positioned within the specified limits. Over the course of several dozen trials, the vehicle successfully navigated (both forward and backwards) to the commanded drum stack, and in every case, positioned the mast within ±2.5 cm of the targeted drum's center line. Moreover, the aisle following scheme kept the vehicle on a straight course down the center of the aisle.

A variant on this experiment was also performed. Here the vehicle was commanded to go to the first stack in the first aisle of the mock facility. This position was the starting vehicle position for one trial of this experiment. During the trial, the vehicle was commanded to move forward to the next stack, which is stack #2, and then the position of the vehicle was recorded on graph paper. This procedure was repeated for stack #3, #4, and #5. Then the vehicle was commanded to move backward one stack, to stack #4, and the position of the vehicle was recorded on the graph paper as usual, and this procedure was repeated to go back to stack #3, #2, and finally back to stack #1. This completed one trial. A baseline run and then five additional runs of this trial were performed. The x position value (x axis runs down the stack of drums) of the vehicle center was calculated relative to the baseline run. These x position values are shown in Table 6-5.

The standard deviation of the x positions is less than 1cm. This variation is within the -2.5 cm to +2.5 cm x position variation observed in the earlier experiment and slightly exceeds the desired envelope.

Table 6-5. Repeatability of Positioning the Vehicle at Drum Centers.

	Drum #1 Location		Drum #2 Location		Drum #3 Location		Drum #4 Location		Drum #5 Location	
	delta x (m)		delta x (m)		delta x (m)		delta x (m)		delta x (m)	
Run Number	forward	back	forward	back	forward	back	forward	back	forward	
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
1	0.0020	-0.0025	0.0090	-0.0020	-0.0015	0.0025	-0.0015	-0.0115	-0.0055	
2	0.0095	-0.0015	0.0185	-0.0070	-0.0060	-0.0020		-0.0105	0.0045	
3	0.0040	-0.0230	0.0070	0.0120	-0.0015	0.0060	-0.0030	0.0115	-0.0080	
4	0.0015	-0.0280	0.0020	0.0160	0.0020	0.0050	-0.0080	-0.0185	0.0070	
5	0.0050	-0.0345	0.0005	0.0095	0.0005	0.0000	-0.0030		-0.0045	
										overall
average	0.0037	-0.0149	0.0062	0.0048	-0.0011	0.0019	-0.0031	-0.0058	-0.0011	-0.0011
median	0.0030	-0.0128	0.0045	0.0048	-0.0008	0.0013	-0.0030	-0.0105	-0.0023	-0.0018
avdev	0.0025	0.01358	0.0053	0.0078	0.0019	0.0026	0.0020	0.0092	0.0049	0.0055
total average		-0.0009								
total median		0.0000								
total average deviation	0.0063	m		min	-0.0345					
from mean				max	0.0185					
stdev		0.00963			range	0.0530				
stdevp		0.00953								
var		0.0001								

As a further illustration of how the drum center finding algorithm works, Figure 6-5 plots time histories of the sonar range data and its computed slope during an aisle navigation maneuver spanning four drum stacks. Cross-hairs mark the points where a drum center was "found".
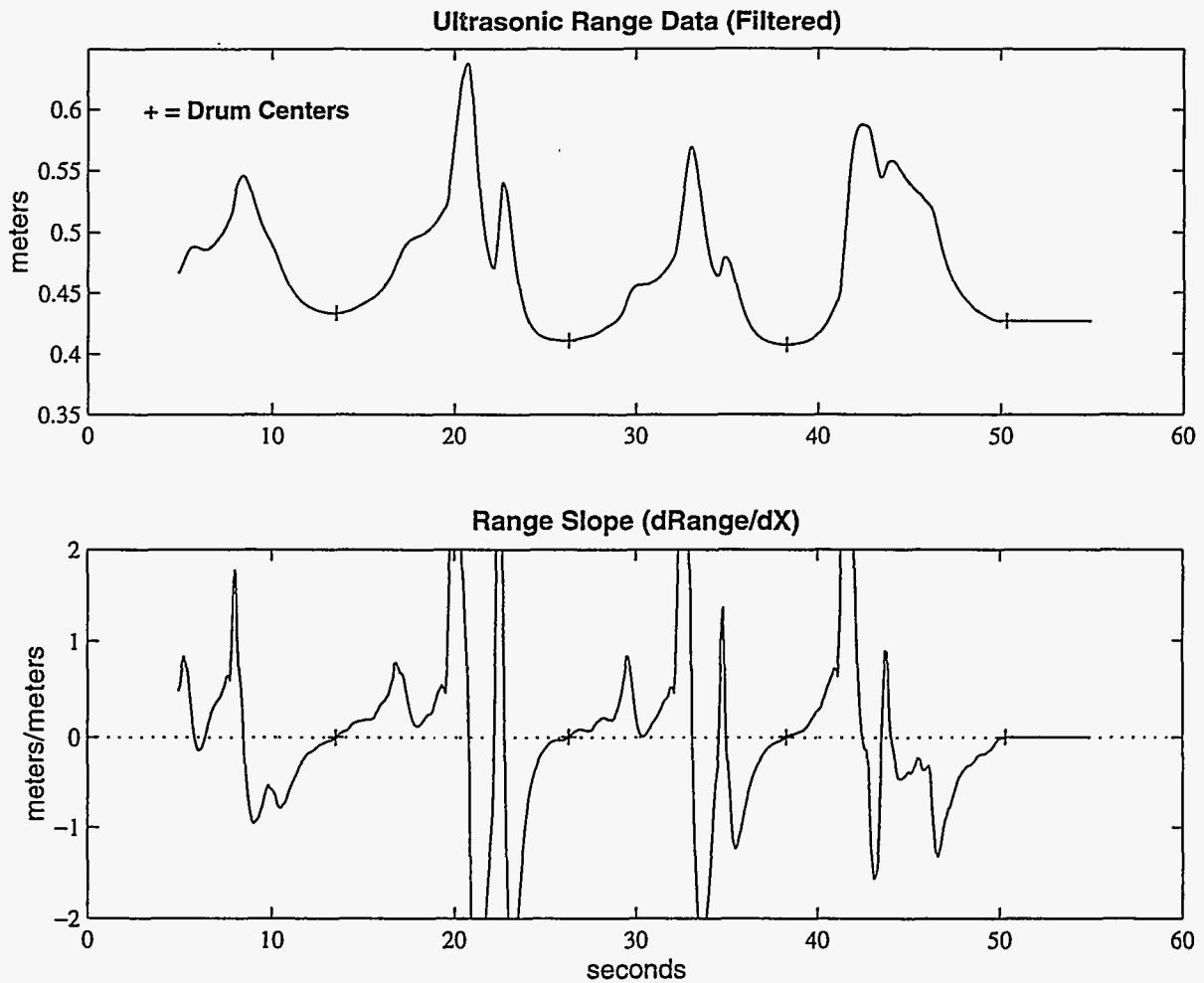
Figure 6-5.   Drum-Finding Time Histories During Aisle Navigation.

6.1.5.3 Finding Aisles

The aisle finding scheme was functionally tested during the integrated testing period. The vehicle was positioned at the mock facility's corridor access point and commanded to find from one to the maximum number of aisles available (three). Over the course of several dozen trials, the vehicle successfully navigated to the commanded aisle, and in general, the aisle finding scheme was found to be very reliable and robust.

6.1.5.4 Obstacle Avoidance

The obstacle avoidance mechanism was functionally tested by commanding the vehicle in all of the possible combinations of navigation mode and direction of travel, with various sized obstacles manually placed in the vehicle path. In all cases when the obstruction was in the ultrasonic field of view, the vehicle stopped short of the obstruction.

6.1.6 Mission Sensing Subsystems

6.1.6.1 Geometric Inspection System

Parametric testing was performed to determine the minimum detectable dent depth and the accuracy of drum tilt determination. Results presented here are limited to the inspection of white and mauve colored drums. For black drums, analysis and testing had shown that the laser-based structured-light system was unable to collect enough data points (too many dropouts) to formulate a reliable geometric drum model. This is due to a combination of two factors: 1) the black surface absorbs too much of the laser stripe's light, and 2) the little amount of light not absorbed is diffused by the drum's glossy surface. The net effect is a dim, fuzzy stripe of light rather than the desired thin, focused stripe of bright light.

6.1.6.1.1 Dent Detection

To parameterize the performance of the inspection system, a number of tests were conducted to determine the minimum detectable dent depth, and to determine the success rate in reporting true dents as well as the rate of reported false, non-existing dents.

For these tests, dents were added to a set of white and mauve colored 55-gallon drums with methods ranging from using a hammer to using a large metal block. Dent depths ranged from 1.1 cm. to 2.5 cm. Using the bottom level sensor suite, a total of 52 trials were conducted in which the drum being inspected had a single dent positioned within ±45° of the drum center. From these tests (see Table 6-6), the sensor exhibited a 100% detection rate for dents 1.6 cm and deeper, and a 0% false positive rate for the inspection of an undented drum.

Table 6-6. Dent Detection Results.

Dent Depth	Trials	Successes	Detection Rate
Undented	17	0	0 %
1.1 cm	7	0	0 %
1.6 cm	24	24	100 %
2.0 cm	11	11	100 %
2.5 cm	10	10	100 %

6.1.6.1.2 Tilt Angle Detection

To determine the accuracy of the GIS sensor measuring a drum's tilt angle, an undented 55-gallon drum was manually tilted from 1 to 8 degrees by placing a block under the bottom rim. The direction of tilt was also varied by placing the block at four points along the rim: left, right, front, and back.

The experimental results of actual tilt angles (in the four directions of tilt) versus measured angles are shown in Figure 6-6. Here, the data points are marked by an 'x' (a perfect measurement would fall on the solid line). The top plot shows the raw data in which tilt angle errors are quite significant (almost 3.5 degrees). The "raw" data consists of tilt angles measured relative to the sensor; thus, the errors can be explained as a result of inherent mechanical bias. Sources of mechanical bias include: alignment errors in the sensor mast as well as the tilt axes, and local deviations or slopes in the floor between the location of the vehicle and the drum pallet. The alignment errors can be calibrated and removed from the measured result; however, the second source of error is more difficult to remove. Since deviations in the floor were known to be insignificant for the testing performed, the mechanical biases were attributed to misalignments in mast and tilt axes. The lower plot of Figure 6-6 shows the bias-corrected measurements. Here, the total error is less than 0.5 degrees.
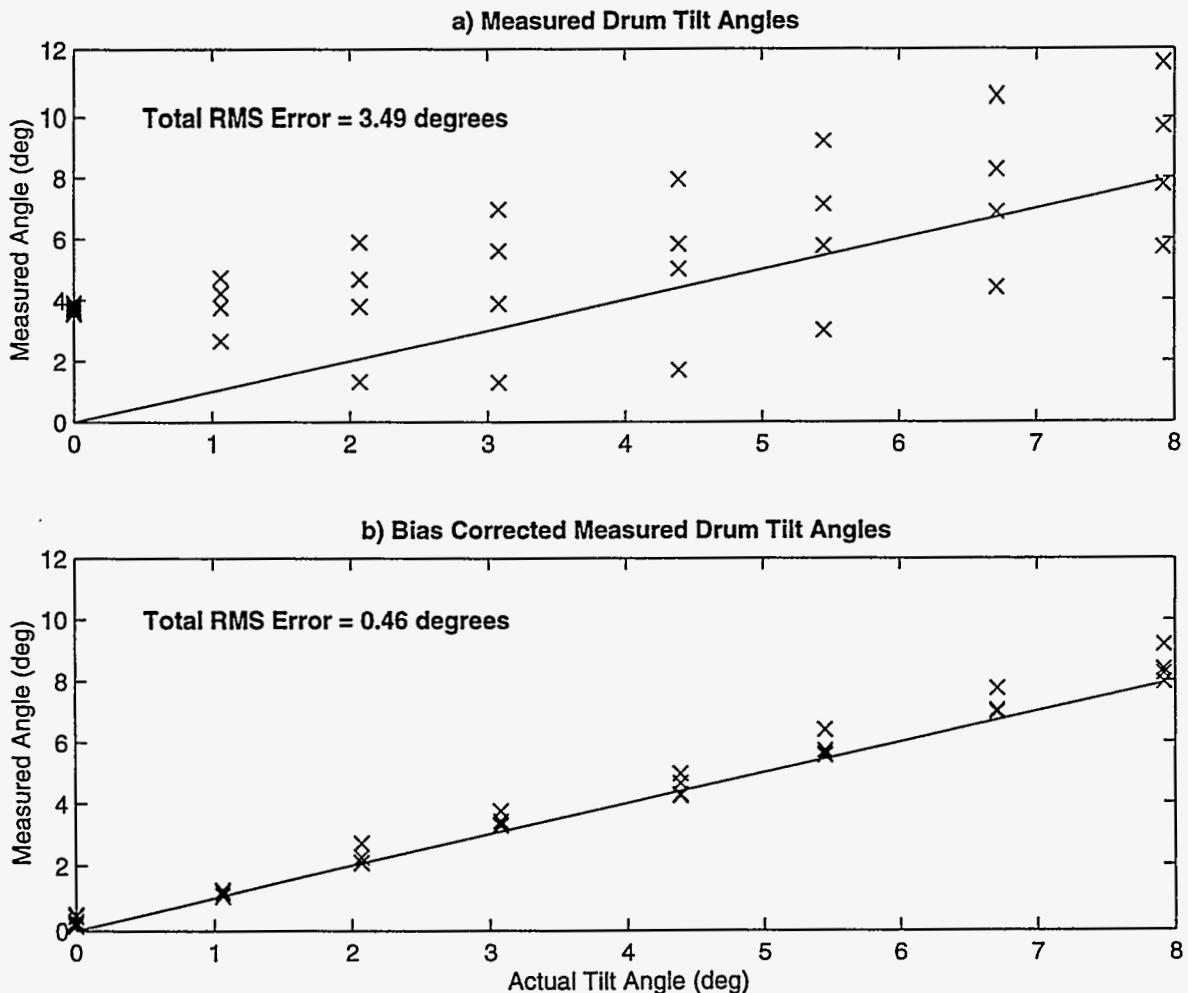
Figure 6-6. Tilt Angle Determination Results.

6.1.6.2 Color Vision System

Image analysis performance and accuracy can be improved by tuning the system for specific site requirements. For example, knowing expected drum condition (new/old, clean/dirty), color, and size of rust and corrosion (small/large) influences several models and novelty detection parameters in the algorithms.

During Phase 2, algorithmic development and testing focused on the classification of drum color and the detection of rust spots (patches). With regard to rust detection, performance was characterized with respect to: 1) location of rust spots on a drum, 2) size of a rust spot, and 3) the shape of rust patches.

Ideally, these tests would be conducted using a large sample of drums populated with a large variety of rust spot sizes, shapes, and locations. However, only a few drums with true rust defects of sufficient size were available for testing in our mock facility. Moreover, it is difficult to generate the required types of rust patches in a timely and controlled manner. Hence, it was decided to perform parametric testing with spots made from red construction paper (see Figure 6-7) of various sizes and shapes (octagons, ellipses, and "splotches"). This provided a systematic way of varying spot size and location. Results are also presented for tests using the small sample of drums available with true rust spots.
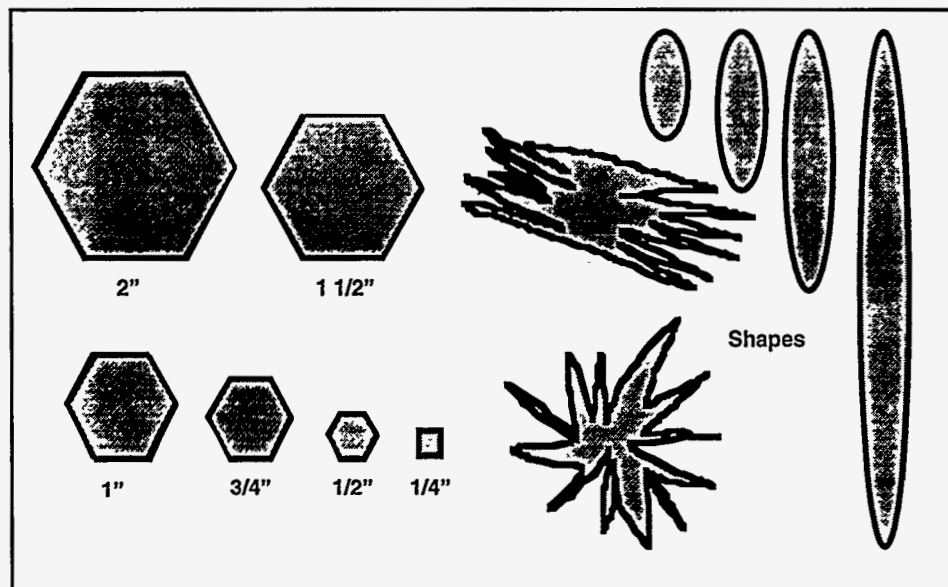
Figure 6-7. Shapes and Sizes of Paper Spots Used for Parametric Testing.

6.1.6.2.1 Drum Color Classification

Classification of drum color is the first step in color analysis for the detection of rust. Using the available set of drums in our mock facility, a 100% classification rate was demonstrated for black, white and mauve drums (based on a sample of 28 drum images).

6.1.6.2.2 Spot Location

The goal was to determine the rate of detection for rust spots as a function of a spot's location along the drum, *i.e.,* what is the system's usable field-of-view. Large paper dots of the same size and shape (2 in. diameter octagons) were taped to the drum top-to-bottom along the vertical center line, along a diagonal, and along the horizontal center lines between ±75 degrees from the vertical center line (see Figure 6-8). Figure 6-9 plots the achieved detection rates based on a sample size of 36 sets of drum images. As can be seen from the plot, the detection rate is reasonable for spots within ±45 degrees; however, spots located along the drum edges are difficult to detect. This is because the spots, as they appear in the digitized image, occupy fewer pixels due to the observed angular distortion. Furthermore, they are not as well illuminated as spots near the vertical center line, resulting in a diminished level of red intensity.
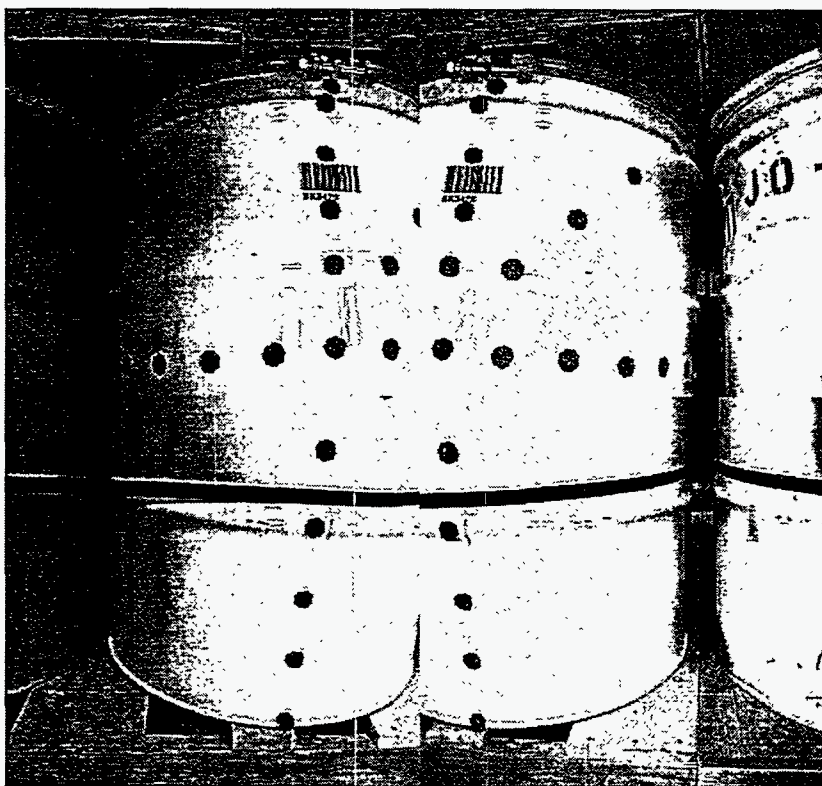
Figure 6-8.   Spot Arrangement for Parametric Testing.
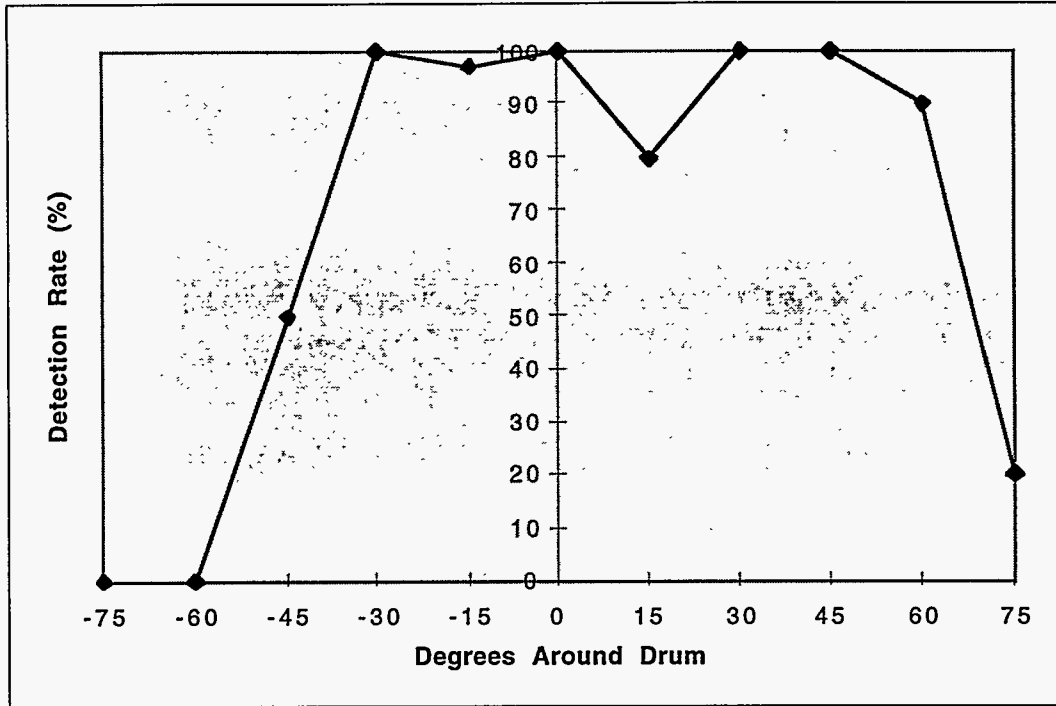
Figure 6-9.   Spot Detection Rates vs. Spot Location.
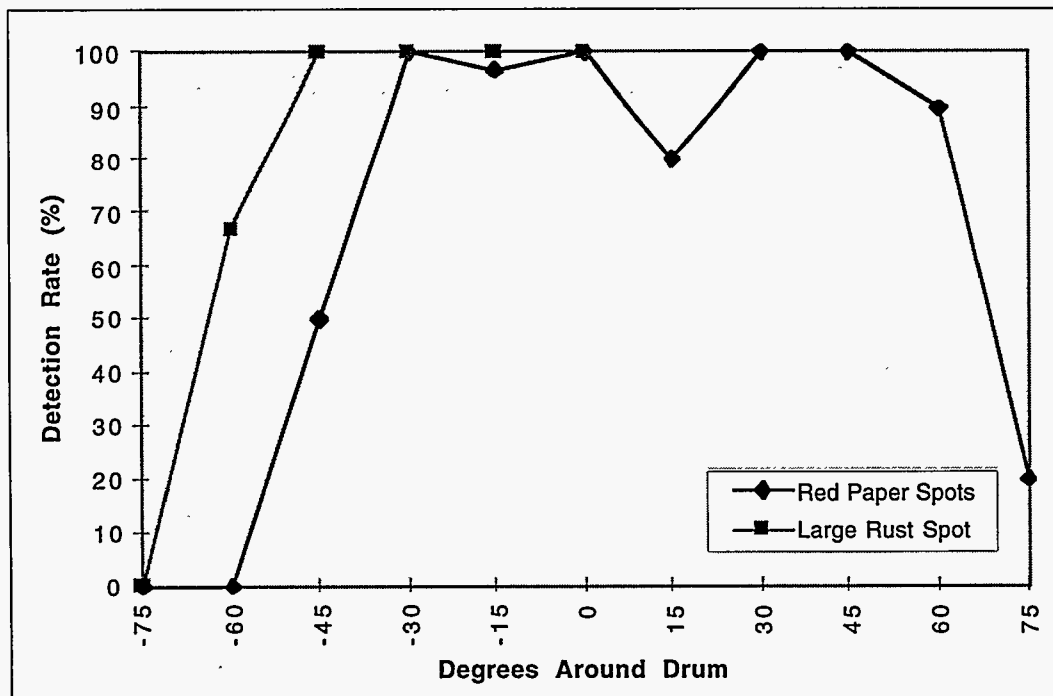
Figure 6-10.   Comparison of Detection Rates Using True Rust Spots.

Using a drum with a true rust spot (approximately 2 in. diameter), six sets of drum images were collected for the rust spot positioned at six locations from 0 to -75 degrees. Figure 6-10 compares the test results for red paper spots and the large rust spot. Similar to the paper spot tests, the detection rate was excellent for the rust spot located within 45 degrees, but poor for the spot located near the drum edge.

6.1.6.2.3 Spot Size

To determine effects of spot size (and ultimately, the minimum detectable spot size), spots of the same diameter were taped to a drum in the same configuration shown in Figure 6-8 and drum images were collected and processed. This test was repeated for each of the spot sizes for both black and white drums resulting in a sample size of 36 sets of drum images. Figure 6-11 plots the results for spots located within ±45 degrees. The average detection rate for spots down to 1/2 in. in diameter was 96% with 2 false positives.
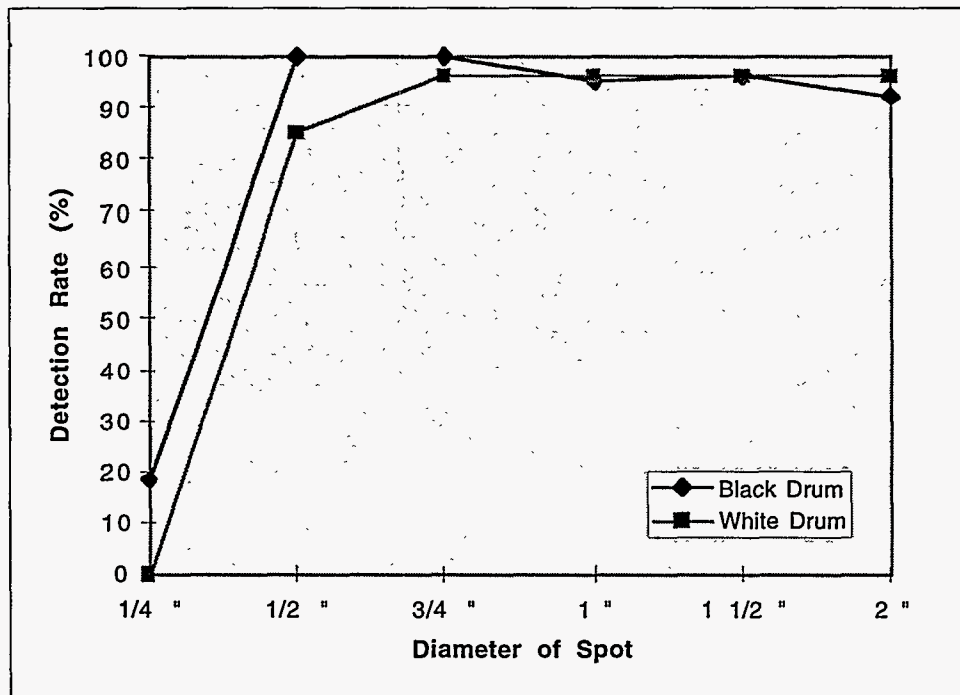
Figure 6-11. Detection Rates for Varying Spot Size Located Within ±45°.

6.1.6.2.4 Spot Shape

To verify the effect of a spot's shape, the elliptical shapes and "splotches" shown in Figure 6-7 were randomly placed on black (see Figure 6-12) and white drums within ±45 degrees of the vertical center line. The detection rates were similar to the cases using octagonal spots.
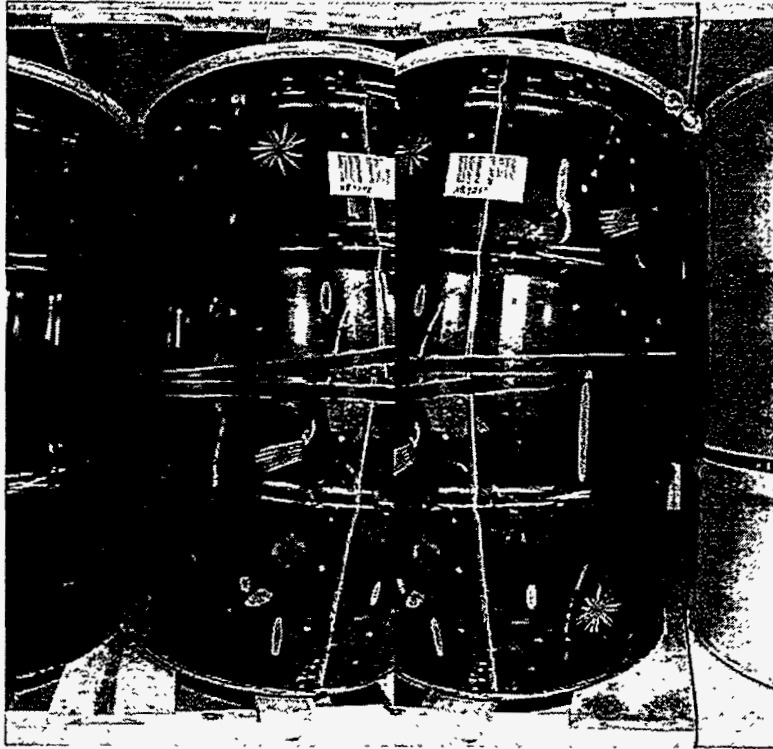
Figure 6-12. Parametric Testing for Spot Shapes.

6.1.6.3 Bar Code Scanner

Testing was performed to determine the reliability of reading bar code labels as a function of label location on the drum. Typically, DOE sites require labels to be placed on the middle third of a drum, within ±30° of the vertical center line. We tested for labels also located on the upper and lower thirds, and out to ±60°. The bar code label specifications were as follows: 2.5 cm. tall, vertical lines (picket fence), 50 mil. narrow bar width, medium density, Code 3 of 9 symbols, 10 alpha-numeric characters. Trials were performed using each sensor at a range of about 60 cm., the nominal inspection range. Based on over 100 trials, a 100% detection rate was demonstrated for labels located with ±45°. Beyond ±45°, the scanner's projected laser stripe becomes too distorted due to the drum curvature. However, the obtained field-of-view far exceeds the requirements for site personnel in regards to label location.

During one end-to-end practice run for the Phase 2 demonstration traversing the complete mock facility, a 97.6% read rate was observed (84 correct reads out of 86 drums with barcodes).

6.1.7 Operator Interface

The operator interface proved adequate for the Phase 2 integrated demonstration and the end-to-end testing leading up to that. All functions were demonstrated there: (a) creating a facility model using the facility model editor, (b) creating a mission plan, and (c) assessing a mission, viewing images of defects found, and printing a report.

6.1.8 Executive

Similarly, the mission executive proved adequate for the Phase 2 integrated demonstration and during the end-to-end testing leading up to that. Speed of inspection for the current vehicle and sensor configuration is limited by the length of time needed to complete the geometric inspection task.

6.2 System-Level Evaluations and Performance and Phase 2 Demonstration

6.2.1 System Level Performance

System-level testing during Phase 2 took the form of end-to-end dry runs of the Phase 2 demonstration in the mock waste storage facility. This facility and an outline of the inspection mission was outlined in Figure 5-33. The Phase 2 demonstration successfully demonstrated:
- Creation of a facility map, using the operator interface.
- Assigning an inspection mission, using the operator interface.
- Note that the initial "baseline" mission was executed the day before the demo day, and was not repeated during the demo day due to time restrictions.
- Execution of the assigned mission. An obstacle was located near the third stack inside row 2. This obstacle was detected and the mission executive aborted inspection of that row and continued with the remainder of the mission.
- Assessment of inspection results, using the operator interface, and also printed report generation.

6.2.2 Needs and Priorities Discussion With DOE Waste Storage Facility Representatives

A meeting was held the day after the IMSS Phase 2 demonstration among all demo attendees to brainstorm and discuss DOE site needs for potential future work. Table 6-7 summarizes the list of needs generated, and High-Medium-Low priorities assigned to them by the two DOE site representatives in attendance that second day.

Table 6-7. Prioritized Needs of DOE Sites.

Index	Fernald	Los Alamos	Item
3	H	H	Pin hole detection
5	H	H	Rust interpretation
6b	H	H	Liquid detection, on the side of a drum
8a	H	H	Viewing span, out to 120 degrees
13	H	H	Non-flush aisle ends
18	H	H	Translucent tents
20	H	H	Automatic recharging
22	H	H	Tracking defects over time, trend analysis
23	H	H	Bubbling paint
24	H	H	Seam inspection
32	H	H	No class 3a lasers
33	H	H	Ignores dust, dirt, extraneous marks
34	H	H	Contamination control (sealed, HEPA filter)
35	H	H	Aisle-end inspection
4	H	M	Black drum dents
25	M	H	Deep scratches
30	M	H	Label presence/change
2	M	M	Alpha detector
6a	M	M	Liquid detection, puddles on floor
7b	M	M	Inspect bolts
8b	M	M	Viewing span, out to 180 degrees
9	M	M	Pallet inspection
14	M	M	Inventory location tracking
17	M	M	Simplicity of operator interface
29	M	M	B25 boxes
31	M	M	Recording keeping, databasing, archiving
1	L	H	Dose rate, gamma
7a	H	L	Rim and chine dents
10	L	L	Inside face inspection
11	H	NA	4-high stacks
12	L	NA	5-high stacks
15a	L	L	Aisle width, 30 inches
15b	L	L	Aisle width, 26 inches
16	L	L	Outdoor inspection
19	L	H	Inter-facility transport
21	L	L	Bulging drums
26	H	NA	Overhanging drums
27	H	NA	Two or three drums per pallet
28	L	L	110 gallon drums
36	H	NA	Heterogeneous rows
37	L	NA	Heterogeneous stacks
38	M	L	Inspection rate of 12,000 drums/week
39	M	L	Operations with people, equipment, activity

(H = High, M = Medium, and L = Low Need)

7. CONCLUSIONS

7.1 Performance

An operational prototype system for automated drum inspection was successfully demonstrated during Phase 2 of the Intelligent Mobile Sensor System program. This new system included an operationally viable vehicle design specifically for DOE WSF environments (*e.g.,* aisle widths, temperature ranges), and featuring real-time planning capability, autonomous tether-free navigation (requiring no facility modifications nor the addition of special landmark targets), obstacle avoidance systems, advanced color vision and structured light inspection sensors integrated with on-board processors for real-time analysis, on-board data storage and automated transfer of results to a remote operator's control station, and an intelligent user interface for supervisory control functions, including mission assignment, mission assessment, and automated report generation. The vehicle contains extensive safety systems, including hard-wired electronics, and software event-driven monitors.

The vehicle was demonstrated end-to-end in a high fidelity waste storage facility mockup. During the integrated testing period, performance of each of the mission sensors was characterized. Table 7-1 summarizes results for the key performance metrics.

Table 7-1. Summary Of Mission Sensors Performance.

Mission Sensor	Performance Metric	Goal	Achieved
Bar Code	*Label detection rate*	100%	100%
Geometric	*Dents:*		
	• Detection rate	95%, depth > 3 cm	100 %, depth ≥ 1.6 cm
	• False positive rate	1%, depth > 3 cm	0 %, depth ≥ 1.6 cm
	Tilted drums:		
	• Detection rate	95%, angle > 5 deg.	100%, angle ≥ 0.5 deg.
	• False positive rate	1%	0%
Color Vision	*Drum color classification (three colors):*		
	• Correct classification	100%	100%
	• Incorrect classification	0%	0%
	Rust spots:		
	• Detection rate	95%, dia. > 2.5 cm	96%, dia. ≥ 1.25 cm
	• False positive rate	10%, dia. > 2.5 cm	10%, dia. ≥ 1.25 cm

The IMSS system provides weekly inspection of mixed waste drums in waste storage facilities, which exist in multiple numbers at multiple sites. Inspections are accurate, consistent, auditable (RCRA), safe (OSHA), and cost effective. The system meets and exceeds DOEs needs by creating a system for autonomous inspection and monitoring of waste drums in DOE facilities, while providing automated

report generation, and a system that is certifiable (DOE, OSHA, EPA), robust and adaptable in operation, and cost effective.

Some of the benefits of the automated IMSS drum inspection system are:

- Reduces operations costs by 75% considering all relevant costs including training, safety, and other overhead factors.
- Improves waste storage operations by creating a more consistent and more auditable inspection process.
- Reduces public and occupational health risks by eliminating 90% of the human involvement and exposure.
- Reduces environmental risks by reducing potential leaks of radioactive and/or hazardous material by having a more frequent, more accurate, quantitative inspection.
- Minimizes secondary waste by eliminating disposable protective clothing used by facility inspectors.

7.2 Limitations and Future Work

Regarding geometric defects, the inspection of glossy black drums is still a problem. Test results proved that only the front 90 degrees of the drum face could be inspected. This surface can contain significant data dropouts. Dirt and dust on the drum increase the angular span. Future work needs to investigate modifications to the current sensing scheme (*e.g.*, increase inspection coverage of black drums by performing GIS inspections at multiple locations, or use two lasers at each suite) or perhaps the development of a new sensor based on a different light spectrum (*e.g.*, infrared).

During Phase 2, inspection for corrosion defects were focused on rust patches. Future work needs to address more types of corrosion, including blistered and bubbled paint. Also, it is necessary to intelligently interpret the grade or severity of these types of defects in order to accommodate the differing acceptability levels among various DOE facilities. Due to the fact that a limited sample of drums with actual defects were available, some of the parametric analyses were based on simulated defects, such as the usage of red paper spots. Future work should attempt to collect defect data on a more extensive, statistically meaningful population of drums with true corrosion defects since it is infeasible to simulate or generate the broad range and variety of defects exhibited in true waste storage facility.

7.3 Derivative Applications

The Phase 2 Intelligent Mobile Sensor System provides a general capability for carrying sensors into hazardous areas and autonomously inspecting or mapping the features of concern. Derivative applications arise from replacing the current sensor mast with task-specific sensor platforms. In this sense, the mobility base supplies power, processing, data storage, and autonomous positioning of the sensor packages in the desired locations. Other reasonable applications include real-time autonomous concrete characterization, sensing in very radioactive locations, and dig-face sensing.

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9. LIST OF ACRONYMS AND ABBREVIATIONS

A	Ampere
ALARA	As Low As Reasonably Achievable
ANSI	American National Standards Institute
ARIES	(South Carolina Universities Research Federation drum inspection robot system)
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	centimeter
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
Hz	Hertz
IMSS	Intelligent Mobile Sensing System (LMA's drum inspection robot system)
IR	Inductive and Resistive
I/O	Input / Output
MHz	Megahertz
LMA	Lockheed Martin Astronautics
m	meter
mW	milliwatt
nm	nanometer
MC&A	Materials Control & Accountability
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
RCRA	Resource Conservation and Recovery Act
RGB	Red Green Blue
R&D	Research and Development
S/W	Software
SWAMI	Stored Waste Autonomous Mobile Inspector (DOE Savannah River drum inspection robot system)
SWIFTS	Stored Waste Information Forecasting and Tracking System
TBD	To Be Determined
TCP/IP	Transmission Control Protocol / Internet Protocol
V	Volt
WSF	Waste Storage Facility
3D	Three Dimensional

10. "TEST" PROGRAM MENUS

The "test" program is a textual menu based program often used during development and testing. It is a convenient way to run various low-level tests and operations with the vehicle. In fact, the system software architecture was designed so that all low-level and developmental test functions are integrated with and accessible from the test program. Only mature test functions are integrated into the test program. Thus some test functions are kept as stand-alone test programs. The "test" program is **not** intended for use in the application; it is for use by the developers only. The graphical use interface provided at the operator console is the system interface for use in the application.

The main menu for the "test" program is shown below. Each menu item is labeled with a number or letter, which the user types to select that item. Some items are submenus, most of which are listed later in this appendix. The other items execute various functions. Functions typically require one or more parameters, and the user is prompted for these values. The right hand side of the main menu screen dump shown, labeled "Battery Parameters", is an independent display generated by the battery monitor task. This display can be toggled on and off from the main menu. When it is on, it will always display on the right-hand side of the screen even when accessing other menus and executing functions. The menus shown here are mostly self-explanatory for a developer and will not be described further (beyond the menu item names themselves).

```
===============================          Battery Parameters
IMSS Phase II Vehicle Control            ---------------------------
===============================          Voltage         (V):    50.5
                                         Current         (A):    -5.2
Subsystem Tests:                         Power           (W):  -262.6
---------------------------              Initial Temp    (C):   +21.6
1. Miscellaneous                         Current Temp    (C):   +21.6
2. Safety Monitor                        State of Charge (%):    70.5
3. Ranging System
4. Navigation                            Actuators are DISABLED
5. COR

System Functions:
---------------------------
n. Enable  actuators
d. Disable actuators
h. Home tilt and mast

Others:
---------------------------
r. Refresh the display
t. Toggle parameter display
e. Exit

Enter choice:  =? [t]
```

Selecting "1. Miscellaneous" from the main menu displays the following submenu. The displays corresponding to each item in this submenu are also shown following.

```
     Miscellaneous Menu
     ------------------
     1. Safety system control
     2. Subsystem power control
     3. Mission Sensor Power Control
     4. Status Panel LED control
     5. Display system states
     e. Exit

     Enter choice:  =? [e]
```

```
     Safety System Control Menu
     --------------------------
     1. Toggle CPU Heartbeat      (now HIGH)
     2. Toggle S/W E-Stop         (now HIGH)
     3. Toggle S/W E-Stop Reset   (now HIGH)
     4. Turn System power off
     e. Return to main menu

     Enter choice:  =? [e]
```

```
     Subsystem Power Control Menu
     ----------------------------
     1. Toggle charge relay       (now OPEN)
     2. Toggle ethernet power     (now OFF)
     3. Toggle LNU system power   (now OFF)
     e. Return to main menu

     Enter choice:  =? [e]
```

```
Mission Sensor Power Control Menu
---------------------------------
1. Toggle COR1 power (now OFF)
2. Toggle COR2 power (now OFF)
3. Toggle COR3 power (now OFF)
4. Toggle GIS  power (now OFF)
5. Toggle BCD  power (now OFF)
6. Toggle ENV  power (now OFF)
e. Return to main menu

Enter choice:  =? [e]
```

```
Status Panel LED Control Menu
-----------------------------
1. Toggle battery temp     LED (OFF)
2. Toggle battery current  LED (OFF)
3. Toggle battery voltage  LED (OFF)
4. Toggle battery  25% SOC LED (OFF)
5. Toggle battery  50% SOC LED (OFF)
6. Toggle battery  75% SOC LED (OFF)
7. Toggle battery 100% SOC LED (OFF)
e. Return to main menu

Enter choice:  =? [e]
```

```
        Current System States:
        ------------------------
        CPU Heartbeat        : HIGH
        S/W E-Stop           : HIGH
        S/W E-Stop Reset     : HIGH
        Charge Relay         : OPEN
        Ethernet Power       : OFF
        LNU Power            : OFF
        COR 1                : OFF
        COR 2                : OFF
        COR 3                : OFF
        GIS                  : OFF
        Bar Code System      : OFF
        Env Sensors          : OFF
        Battery Temp     LED: OFF
        Battery Current  LED: OFF
        Battery Voltage  LED: OFF
        Battery  25% SOC LED: OFF
        Battery  50% SOC LED: OFF
        Battery 100% SOC LED: OFF

        Hit Return when ready. =? [ ]
```

Selecting "2. Safety Monitor" from the main menu displays the following submenu. The displays corresponding to a few items in this submenu are also shown following.

```
        Safety Monitor Menu
        -------------------
        1. Start tSysmon
        2. Stop tSysmon
        3. Set battery parameters
        4. Display battery parameters
        5. Set verbosity level (now 1)
        e. Exit

        Enter choice:  =? [e]
```

```
Select battery parameter to set:
--------------------------------
1. Initial Temperature
2. Current Temperature
3. Voltage
4. Capacity
5. Current
6. Clear all conditions.
e. Exit

Enter choice:  =? [e]
```

```
Battery Parameters:
---------------------------
Voltage          (V):  50.2
Current          (A):  -5.2
Temperature      (C):  21.7
State of Charge (%):   0

Type <CR> to return to main menu.
```

Selecting "3. Ranging System" from the main menu displays the following submenu.

```
Ranging System Menu
-------------------
1. Start
2. Stop
3. Set new blank inhibit delay  (800 us)
4. Set new delay between pings  (0 frames)
5. Display ranges once
6. Display ranges continuously
7. Clear all range values
8. Set vehicle direction
9. Set verbosity level          (1)
e. Exit

Enter choice:  =? [e]
```

Selecting "4. Navigation" from the main menu displays the following submenu. The displays corresponding to some items in this submenu are also shown following.

```
Navigation Menu
---------------

Commands:
1. Find relative aisle
2. Find relative stack
3. Move to absolute position
4. Move to relative position
5. Set new world position
6. Turn Collision Avoidance On.

Set Up:
n. Set Navigation Mode
m. Set Mast Position
g. Set Wheel Control Gains
v. Set Verbosity level (now 2)

Others:
e. Exit

Enter choice:  =? [5]
```

```
Select the Navigation Mode:
---------------------------
1. Follow           ** Current **
2. Free Space
3. Docking
4. No Change

Enter choice:  =? [4]
```

```
Select the Mast Position:
------------------------------
1. Mast LEFT,    looking RIGHT    ** Current **
2. Mast RIGHT,   looking LEFT
3. Mast CENTER,  looking RIGHT
4. Mast CENTER,  looking LEFT
5. Force 'Mast As Is' command
6. No change in command

The mast will be moved during the next vehicle move

Enter choice:  =? [6]
```

Selecting "5. COR" from the main menu displays the following submenu.

```
COR Menu
--------

Commands:
1. run COR inspect
2. grab 2COR PA images for sensor suites 0&1
3. auto-grab GIS+2COR images for sensor suites 0&1

Set Up:
5n. toggle power for COR sensor suite n
6. toggle power for all GIS sensor suites
7. set tilt angles
8. tilt joystick

Others:
-1. Exit

Enter choice:  =? [20]
```

11. IMSS PHASE 2 LEVEL A SPECIFICATION DOCUMENT

IMSS Phase 2 A-Specification
Revision 1.23, Date 2/7/1994

1.0 Identification

The IMSS (Intelligent Mobile Sensor System) program is a research, development, and demonstration program for automated inspection of waste storage containers in a warehouse-like facility at DOE sites. The product of this effort will be a robotic device (Mobile Robot Drum Inspection System (MORDIS)) with enhanced intelligence and maneuverability capable of conducting routine inspection of stored waste drums. There are two main components of the system: a mobile robot and a control station.

Equipped with enhanced on-board intelligence and maneuverability, the mobile robot is capable departing on an assigned mission, navigating through narrow aisles between rows of drums stacked on pallets, and avoiding obstacles along the way. Equipped with an integrated sensor suite, the robot will gather data to identify and report anomalous drum conditions. These defects include rust spots, rust streaks, areas of corrosion, dents, tilted drums, drums out of place, and missing barcode identification labels. Also recorded are data from radiation and gas detectors, a history of the robot's path and what portion of the mission may have been modified or aborted due to environmental constraints. Having completed an inspection mission, MORDIS returns to its home base, docks with a battery recharger, and transfers the collected data across an Ethernet communication link to the operator's console located at the central control station.

From the control station, the operator works with an intelligent graphical user interface to review and direct the inspection process for a number of storage facilities. When a robot's mission data has been downloaded, he/she verifies the actual route of the robot against its assigned route and reviews the data collected for any reported defects. A more detailed inspection report is generated and printed, notifying the operator of defective drums which must be resolved before the next inspection cycle. For the next leg of an inspection, the operator can confirm a pre-selected mission assignment or override and designate a different mission. Included is the ability to assign the inspection of specific drums or an entire group (aisle). An intelligent planner will generate the inspection sequence and allow the operator to preview the plan. Finally, the verified inspection plan is downloaded to the robot and permission to depart after recharging is granted.

At the end of an inspection cycle, a full report of all the inspections for each storage facility is compiled and printed. Because drum defects are recorded in a database, MORDIS is capable of tracking the condition of drums over time. In addition, identification of incompatible waste storage is possible.

1.1 Scope

The IMSS Mission Requirements Specification establishes the mission requirements for the inspection system that will be demonstrated at the Hanford mixed waste storage facility.

1.2 Operational Scenario (DRAFT)

An operator on duty, is notified at his operator's console that there is newly arrived E-mail. He clicks on the ReadMail icon:

```
-------------------------------------------------------------
From: MORDIS (MObile Robot Drum Inspection System)
To: console@john.hanford.eeg.gov
Subject: Inspection mission complete at Bldg. D

Waste Storage Bldg.:  D
Mission Assignment:   Inspect Aisle 3
Drum Count:           912 expected, 912 inspected
Reported Defects:     2

Current Status:

o Inspection complete and recharging for next mission.
o Ready to download defect report.
o Waiting for next Mission Assignment.
-------------------------------------------------------------
```

From the graphical user interface running on the console, the operator specifies Building D and launches the ``Mission Assessment'' window. Displayed is a plan view of the building and the aisles of stacked drums. Shown in blue are those drums already inspected for the current inspection cycle, and in gray, drums yet to be inspected. Flagged in red are the two drums reported defective in Aisle 3. Also shown is a trace of the vehicle's path during the inspection.

Clicking the ``Review Defect Report'' button, a summary is displayed for the first drum, listing its location, barcode identifier, and the type of defect. Also displayed is an accompanying color image which highlights a long rust streak along the upper quarter of the drum. After reviewing the second defective drum, the operator clicks the ``Print'' button. This report printout will be used the next day by a human inspector to help locate and resolve the defective drums.

Next, the operator launches the ``Mission Assignment'' menu. Displayed is a facility map with Aisle 4 highlighted as the recommended area to be inspected next. He confirms this to be okay, and selects the ``Preview Inspection'' button to see a simulation of the route MORDIS will follow. Satisfied, the operator selects ``Download Mission'' and okays MORDIS's request to depart after recharging is complete.

2.0 Environmental Characteristics

The IMSS vehicle shall be capable of operating and performing its required inspection tasks in the following environment.

2.1 The floor will be flat with seams less than 2.5 cm wide.
2.2 Ramps will be less than or equal to 15 degrees.
2.3 Aisles
    2.3.1 Aisle width: greater than 76.2 cm. (30 in.).
    2.3.2 Aisle length: less than or equal to 122 m (400 ft.).
    2.3.3 Minimum free space at one end of aisle: 1.8 m (6 ft.).

2.3.4 Aisles may be dead end.

2.3.5 No more than 1 missing stack of pallets in an aisle.

2.4 Waste drums

2.4.1 Will be stacked 3 high on pallets.

2.4.2 Drum sizes will include 55 and 85 gallon drums. The inspection system can be tailored for other drum sizes.

2.4.3 Pallets will be made of wood and will be 13 cm +/- 2 cm high.

2.4.4 Drum edge will be within +/- 5 cm from edge of pallet.

2.4.5 Drums will be aligned vertically +/- 2.5 cm.

2.4.6 Drum colors will include galvanized steel, black, white, yellow, mauve, brown, gray, and red. The inspection system can be tailored for other colors.

2.5 Room temperature will be between -17C and 40C (+2F and 104F) .

2.6 Containment berms may exist around the storage perimeter - 10 cm high, 20 cm wide. Berms will be at least 1 m away from front of drums. If berms are greater than 10 cm. high then ramps will be provided.

2.7 A CAD-based map of each facility will be supplied which will show all relevant features such as walls, columns, and other fixed obstacles with an accuracy of 15 cm. Information will be supplied indicating the number of drums, and the arrangement of drum stacks (number of aisles, aisle length).

2.8 An Ethernet connection will be available linking the operator interface and the docking station.

2.9 115 VAC, 40 amps will be available for the docking/charging station.

2.10 The humidity will be less than 90%

3.0 System Requirements

The IMSS system consists of the following subsystems: Control Station, Mission Inspection Sensors, Vehicle, and Mission Support Equipment. The system shall have appropriate communications interfaces between subsystems. The system shall be autonomous and untethered.

3.1 Control Station

The Control Station allows the storage facility operator to direct and review the inspection process and is the primary means of exchanging mission-relevant data with the vehicle. The Control Station shall provide the following features and capabilities.

3.1.1 Menu-based Graphical User Interface (GUI).

3.1.2 Mission assignment. Interactive, semi-automated planning and initiation of an inspection mission. Operator will play supervisory role in the selection of drums to be inspected.

3.1.3 Mission assessment. Operator will be able to review an inspection mission for completeness, possible anomalies that may have occurred (e.g., blocked aisles), reported drum defects (textual summary along with visual display of drum images).

3.1.4 Report generation. Printouts will be generated summarizing a single inspection mission in addition to the compilation of all drum defects reported during an inspection cycle.

3.1.5 Defect report archival. Each mission's defect report will be archived on a mass-storage device with a date and time stamps of the mission included. To prevent accidental removal, delete access will be restricted to selected personnel.

3.1.6 Facility model database administration. User must be able to easily create necessary database information for new storage facilities as well as modify existing ones to reflect important

features (e.g., changes in drum layouts, known obstacles to avoid, etc.).

3.2 Mission Inspection Sensors

The vehicle shall be capable of inspecting 12000 drums per week and shall perform the following tasks.

3.2.1 Rust and Corrosion Inspection

The rust and corrosion inspection system shall inspect the surface area normally viewable by an inspector (90% of the front half of the drum). New rust and corrosion shall be reported, and weekly changes in visible defects shall be tracked and reported. Existing, acceptable defects (e.g., normal wear and tear) are identified in the Defect Log. Defects have quantitative (e.g., size) and qualitative (e.g., brightness) features. Qualitative inspection criteria shall be defined by DOE-provided sample images showing acceptable and unacceptable rust, corrosion (e.g., flaking and pitting), and streaks. For quantitative inspection criteria, the system shall locate and identify the following visible defects on drum surfaces:

3.2.1.1 Rust spots with major axis greater than 1.0 cm: At least a 95% Probability of correct Detection (POD) with less than 10% false positives.
3.2.1.2 Corrosion spots with major axis greater than 1.0 cm: A 95% POD with less than 10% false positives.
3.2.1.3 Rust streaks having minimum width of 0.5 cm and minimum 10:1 length-to-width ratio: A 95% POD with less than 10% false positives.

3.2.2 Geometric Inspection

The geometric inspection system shall inspect the viewable area from 50 cm in front of the drum and locate and identify the following drum defects:

3.2.2.1 Drums displaced more than +/- 10 cm from expected location relative to an adjacent drum.
3.2.2.2 Dents defined as inward deviations from the nominal drum surface greater than 3 cm in depth and 100 square cm area (95% POD with 1% probability of false positives per drum). Highly absorptive or specular reflective drum surfaces may limit inspection area or prohibit inspections.
3.2.2.3 Drums tilting by more than 5 degrees (95% POD with 1% probability of false positives per drum).
3.2.2.4 Drum missing from expected location.

3.2.3 Drum Identification

3.2.3.1 The barcode labels shall be in the middle third of the drum, facing the aisle, and unobstructed.
3.2.3.2 The bar code reader shall read labels with 2.5 cm tall vertical bars, 50 mil narrow bar width, medium density, Code 3 of 9 symbols, 10

alpha-numeric characters.
3.2.3.3 Missing barcodes shall be reported as defects.

3.2.4 Environmental Sensors

3.2.4.1 Hydrogen sensor TBD
3.2.4.2 Radiation sensor TBD

3.2.5 Defect Log

3.2.5.1 During each inspection mission, an on-board defect log shall be generated, capable of storing information (drum id, defect type, size and location) on 6000 defects per mission.
3.2.5.2 An image of each defective drum shall be saved for operator viewing and report.

3.3 Vehicle

3.3.1 Navigation

3.3.1.1 The navigation system shall have an obstacle avoidance system capable of sensing and avoiding obstacles on the floor that are over 10 cm high.
3.3.1.2 The vehicle shall be capable of navigating autonomously.
3.3.1.3 The vehicle shall automatically return to the recharge station.
3.3.1.4 The navigation system shall not require permanent or excessive modifications to the facility.

3.3.2 Mobility and Control

3.3.2.1 The mobility system shall be capable of backing up in an aisle.
3.3.2.2 The vehicle shall have a turn radius sufficient to turn from one aisle to another.

3.3.3 Executive

3.3.3.1 A mission executive software module shall coordinate all vehicle motion and mission sensor processes, ensuring that reported defects are properly correlated with the facility model database.
3.3.3.2 In the event of a recoverable anomaly (e.g., a detected aisle obstruction), the mission executive shall generate and execute a contingency plan to continue and complete as much of the original inspection plan as is possible.

3.4 Mission Support Equipment

3.4.1 The system shall include a sub-system for retrieving and transporting a failed (possibly powerless) vehicle from the storage warehouse.
3.4.2 The system shall include a Docking/Recharge system for communicating with the operator interface.
3.4.3 The system shall include a Docking/Recharge system for battery recharge.

4.0 System Safety

System safety engineering principles shall be applied throughout the design, manufacture, and test of the IMSS systems and components. The IMSS system design shall be such that hazards to personnel, to the system, to facilities, and waste drums are either eliminated or controlled throughout all phases of the system life cycle.

5.0 Decontamination

5.1 All external surfaces shall be washable.
5.2 Wheels shall be easily removable.

6.0 Maintainability

6.1 Normal maintenance shall be completed in one 8-hour shift per week.
6.2 In general, mechanical and electrical systems shall be maintainable with no special tools. If special tools are required, they will be provided.

7.0 Portability

7.1 The vehicle shall have lifting lugs and tie down lugs.
7.2 The sensor mast shall be manually stowable.

Notes:
1. All system components and subsystems shall be designed and built in accordance with best commercial practices.
2. Mission sensor subsystems will be designed with an emphasis on modularity.