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**Intelligent Mobile Sensor System for Drum Inspection and
Monitoring - Volume II**

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Abstract

The objective of the Intelligent Mobile Sensor System (IMSS) project was to develop an operational system for monitoring and inspection activities for waste storage facility operations at several DOE sites. Specifically, the product of this effort was 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 creates and maintains 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 was separated into three phases of which phase three 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 employed an integrated design that considered operational requirements, hardware costs, maintenance, safety, and robustness. The final phase has demonstrated the commercial viability of the vehicle in operating waste storage facilities at Fernald, Ohio and the Idaho National Engineering Laboratory (INEL).

This report summarizes the system upgrades performed in phase 3 and the evaluation of the IMSS Phase 3 system and vehicle. Several parts of the IMSS Phase 1 and 2 Topical Reports, which describe the requirements, design guidelines, and detailed design of the vehicle, are incorporated here, with modifications to reflect the changes in the design and the new elements added during the Phase 3 work. The specific enhancements of note are the addition of the Automated Baseline Change Detection (ABCD) inspection capability, the construction and integration of a fourth mast segment for use in the INEL facility, the redesign of the operator workstation to improve functionality, and the improvement in navigation and ranging robustness based on experiences at Fernald. Additionally, the field testing performed at Fernald, Ohio and the system installation performed at INEL are discussed and system performance is evaluated for the fielded system.

Acknowledgments

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Credit is due to Pete Berardo of Lockheed Martin as well as Jeremy Wilson and Shyan Ku of Kinetic Sciences Incorporated for the development of the Phase I Automated Baseline Change Detection (ABCD) software and their assistance in porting this code to the vehicle.

Engineering credit is due to the team involved in this work at Lockheed Martin Astronautics. For the prototype development, Mat Ramey developed the real-time software for the mission executive, bar code inspection, database libraries, and provided the system design and software support for the control station. Mark Roberts developed the real-time software for navigation and obstacle avoidance, the system safety monitors, and was the electronics design lead. Dan Layne and Ray Rimey designed the color vision sensor and corrosion detection algorithms; Chris Voth was responsible for the structured light sensor design and algorithm development. Brad Haack developed the articulation control for the mast and tilt axes, and the battery monitor interface. Mechanical design of the vehicle was done by Scott Mickey, Brad Haack, Wendell Chun, and Val Gregory. Bob Glade and Tim Charles built the custom electronics and were critical to the final integrated vehicle assembly. Glen Sanders developed the motion control board interface libraries. Rob Monical and Scott Web developed the control station's graphical user interface. The Phase 1 team included: John Spofford, Mark Roberts, Bill Hoff, Dan Layne, Amy Geoffrey, Bob Glade, Tim Charles, and Judith Stewart. The final development and integration were performed primarily by Bill Klarquist and Ray Rimey, including upgrades and improvements in the sensor system, navigation system, and computing system.

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1. EXECUTIVE SUMMARY

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 consisted 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, of the project involved the development of 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 culminated in extended field testing and demonstration and enhancements to the vehicle and system to prove commercial viability and robustness.

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.

Phase 3. The engineering effort focused on improving the mission sensing capability, improving navigation robustness, and integrating ABCD; and culminated with extended field trials at the Fernald Environmental Management Project (FEMP) and the Idaho National Engineering Laboratory (INEL) Radioactive Waste Management Complex (RWMC). 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.

2. INTRODUCTION

This report documents basic requirements and background material for the DOE drum inspection problem, and describes the design upgrades and evaluation of the IMSS Phase 3 vehicle. In this section an introduction to the complete IMSS system is provided.

2.1 Introduction to the IMSS System

The IMSS system has three main components: a mobile robot; an operator's control station; and a docking station. The mobile robot is capable of autonomously departing from the docking station 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 gathers data to identify and report anomalous drum conditions. These defects include rust spots, rust streaks, areas of corrosion, significant areas of change on the drum face, dents, tilted drums, drums out of place on a pallet, missing barcode identification labels, and barcode labels inconsistent with the site-wide drum database. After completing an inspection mission, the IMSS vehicle returns to its docking station to recharge its batteries and download data across an Ethernet communications link to the operator's control station. At the control station, an operator utilizes a graphical user interface to review the results of an inspection mission. The operator also uses the control station to define and schedule subsequent inspection missions for the robot to perform.

A single control station services multiple waste storage buildings, as illustrated in Figure 2-1. The control station contains a model of each building, a database of all the drums for each building, and a database of defects located in each building. 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. Each waste storage building 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 the hardwired site-wide ethernet. In order to better coordinate vehicle operations with human operations inside the warehouse, the docking station also includes a remoter radio control panel from which "pause" and "emergency" stop signals can be sent to the vehicle. An option exists to display a live video feed from a camera on the vehicle to a TV monitor at the docking station, so a visitor can get some feeling for what the robot is doing (the IMSS system does not itself use this video data).

Figure 2-1. A single, central control station controls multiple vehicles in multiple buildings.

2.2 The IMSS Vehicle

The IMSS vehicle is shown in Figure 2-2. Key features of the IMSS system include:

- Mobility platform measuring 21 inches wide by 39 inches long, allowing navigation through aisles down to 27 inches wide. The current operational system is validated down to 30 inch aisles -- operations in narrower aisles requires new mounting fixtures for certain ultrasonic sensors on the vehicle body.
- Articulated sensor mast hosting four sensor suites, allowing simultaneous viewing of a four-high stack of drums and non-simultaneous viewing of the fifth level of five-high stacks. (The figure shows an older variant of the IMSS vehicle before the addition of the fourth sensor suite on a mast extension.)
- Self-contained battery power system providing 4 kW-hours at 48 volts, with 5-6 hours of operation at room temperature on a single charge.
- All planning and scheduling of vehicle operations, and all drum image analysis is done on-board the vehicle in real-time.
- Data storage of defect logs, databases, and images of drums containing detected defects to an on-vehicle hard disk drive.
- Feature-based navigation using only pre-existing building landmarks such as pallets and drums.
- 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 and blocked aisles.

Some of the key components of the IMSS system are summarized on the following pages.

Figure 2-2. The IMSS vehicle.

Figure 2-3. Close-up of lower sensor suite on the IMSS vehicle's sensor mast.

Mounted on the vehicle's sensor mast are four identical integrated sensor suites that gather data to identify and report anomalous drum conditions. A photograph of the lower-level sensor suite is shown in Figure 2-3. The IMSS vehicle can detect and report three categories of drum defects: 1) bar code defects, 2) geometric defects, 3) corrosion defects and any other changes on a drum's face. Moreover, the IMSS system 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.

2.2.1 Bar Code Reading

Bar code labels can be used to identify and track waste storage drums. A drum's bar code 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 in each sensor suite, allowing the scanner's laser stripe to be scanned over any portion of a drum face. Decoder units are mounted inside the vehicle's body and interface with the vehicle's mission processor through a serial port. The system can be configured to report a "defect" 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, detailed inventory tracking could also be performed. The IMSS system can also be configured to read and use bar code identifiers when they exist, but otherwise not consider it a "defect" if one is missing or can not be read. The IMSS system can also be configured to never read bar code labels and always use an identifying label automatically generated based on a drum's position in the building. (Note that for a drum with no other defects except a missing/unread barcode label, the IMSS system does not store color images of the drum for later viewing at the operator's control station. Such color images are stored only when a drum has either geometric defects or corrosion defects.)

2.2.2 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 Class II *structured light system*. It consists of a Class IIIa laser line (i.e., stripe) projector, a video camera and a frame grabber. As a laser stripe is scanned across the surface of a drum, video images are acquired and sent to on-board image processors that extract the location of the stripe in the video images. Based on triangulation of the extracted stripes, a 3-dimensional image of the drum contour is generated and then fitted to a model of a cylinder. A patch of 3-dimensional data that lays underneath the model 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 following parameters of interest are recorded: the location and size of a dent, the drum's angle of tilt, and any abnormal positional displacement on the pallet or spacer rings. Color images of defective drums are stored to a hard disk for later viewing at the operator's control station.

2.2.3 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 consisting of two pairs of color video cameras and halogen lamps. Four or 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, their size and locations are recorded. Color images of defective drums are also stored to a hard disk for later viewing.

The IMSS vehicle's *Automated Baseline Change Detection* (ABCD) system detects any significant changes in the visual appearance of the face of a drum. It complements the original color-based corrosion detection system, increasing the defect detection performance of the IMSS system. The ABCD system operates on 4 color images and reports similar defect results as does the corrosion detection system.

Figure 2-4. The IMSS control station.

2.3 The IMSS Control Station

During an inspection mission, all vehicle activity is coordinated by the vehicle's on-board mission executive software and its real-time planner. However, site personnel are involved to supervise operations before and after a mission. An ideal arrangement is to have a single primary operator for the system, responsible for performing mission assignment and mission assessment operations. This is done through a graphical user interface from the centralized IMSS control station, shown in Figure 2-4.

File Edit Facility Window Reports

Facility: RMC 628 Date: Monday March 3 1997

Messages: Vehicle is READY

Inspection Name	Rows	Drums	Status	CIR	ALCD	GIS	Bar	Start	Finish	Duration
Inspection1	1	2	Completed	11	0	4	0	15:20:09	15:59:06	--:17:--
Inspection2	6	104	Pending	0	0	0	0	--:--:--	--:--:--	05:33:--

Edit/View Assignment View Inspection Results Download to Vehicle Execute Inspection

Figure 2-5. Main Screen of the IMSS operator interface.

The graphical user interface that the operator sees initially, called the Main Screen, is shown in Figure 2-5. This screen shows the inspection missions scheduled or already completed for a specified day of the year, and is the starting point for all other functions the operator may perform.

NA	NB	NC	ND	NE	NF	NG	NH	NI	NJ	NK	NL	NM	NN	NO	NP	NQ	NR	NS	NT
len	len	len	len	len	len	len	len	len	len	len	len	len	len	len	len	len	len	len	len
10	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	10

20' 0" central corridor width

0' 0" N/S row alignment

SB	SC	SD	SE	SF	SG	SH	SI	SJ	SK	SL	SM	SN	SO	SP	SQ	SR	SS	ST
len	len	len	len	len	len	len	len	len	len	len	len	len	len	len	len	len	len	len
11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	10

- 5' 0" docking station relative position

8' 0"

Facility: RMMC_628

Save

Exit

Figure 2-6. IMSS Facility Model Editor.

The *Facility Model Editor* function of the control station is normally only used occasionally. It allows an operator to specify the physical layout of the rows of drums inside the building where the IMSS vehicle is installed, as shown in Figure 2-6. The vehicle uses this information to help drive around inside the building.

Edit		Help			
	Row-Side	Inspected	Last Inspected	Begin Grid	End Grid
	SB-R	0	Unknown	6	12
	SB-L	0	Unknown	12	6
	SC-R	0	Unknown	6	12
	SC-L	0	Unknown	12	6
	SD-R	0	Unknown	7	12
	SD-L	0	Unknown	12	7
	NB-L	0	Unknown	11	12
	NB-R	0	Unknown	12	11
	NC-L	0	Unknown	11	12
	NC-R	0	Unknown	12	11
	ND-L	0	Unknown	11	12
	ND-R	0	Unknown	12	11

OK
Apply
Cancel

Figure 2-7. IMSS Mission Assignment Screen.

The *Mission Assignment* function of the control station allows an operator to specify an exact sequence of rows to be inspected, or simply to confirm a default assignment based on the building's current state of inspection. Figure 2-7 shows a sample of the Mission Assignment interface.

File View									
	Item ID	Kou	Grid	Level	Pos	Inspection Defect Type	Inspection Status	Inspection Date	Inspection Description
	IRDF00023543A	SB	11	2	0	Rust Patch	New	Unknown	A= 1.4 D=(202,40)
	IRDF00023543A	SB	11	2	0	NoDrum	New	Unknown	Drum not found
	IRDF0002351310	SB	11	1	4	NoDrum	New	Unknown	Drum not found
	IRDF0002351310	SB	11	1	4	Rust Patch	New	Unknown	A= 0.8 D=(180,313)
	IRDF0002351210	SB	11	1	4	Rust Patch	New	Unknown	A= 2.1 D=(205,457)
	IRDF0002351510	SB	11	1	4	Rust Patch	New	Unknown	A= 0.2 D=(320,403)
	IRDF0002351510	SB	11	1	4	Rust Patch	New	Unknown	A= 0.3 D=(253,407)
	IRDF0002351510	SB	11	1	8	Rust Patch	New	Unknown	A= 0.3 D=(183,402)
	IRDF0002351510	SB	11	1	0	Rust Patch	New	Unknown	A= 0.5 D=(203,310)
	IRDF0002351510	SB	11	1	0	Rust Patch	New	Unknown	A= 0.4 D=(203,320)
	IRDF0002351510	SB	11	1	0	NoDrum	New	Unknown	Drum not found
	IRDF0002351510	SB	11	1	8	Rust Patch	New	Unknown	A= 0.5 D=(312,455)
	IRDF0002351245	SB	11	3	4	Rust Patch	New	Unknown	A= 0.2 D=(313,453)
	IRDF0002351510	SB	11	2	4	NoDrum	New	Unknown	Drum not found
	IRDF0002351510	SB	11	2	4	Rust Patch	New	Unknown	A= 0.8 D=(191,310)
<input type="button" value="New Images"/> <input type="button" value="Change Status"/> <input type="button" value="Select Column heading to Sort by Column"/> <input type="button" value="Close"/>									

Figure 2-8. IMSS Mission Assessment Screen.

The *Mission Assessment* function of the operator interface allows an operator to review a mission's defect logs, display color images of defective drums, and generate a report summarizing the mission along with a list of reported defects. Figure 2-8 shows a sample of the Mission Assessment interface.

Figure 2-9. Boxes are drawn around detected corrosion defects in the composite image of a drum that the operator can summon for verification purposes.

A color image of every drum with geometric or corrosion defects is stored on the vehicle's hard disk for later viewing at the operator's control station. Figure 2-9 shows a sample of the processed image that is stored. It is the composite of four images. Corrosion defects are outlined by red boxes (defects detected based on color) or green boxes (defects detected based on changes seen in the drum since the last inspection).

Figure 2-10. The IMSS docking station.

2.4 The IMSS Docking Station

The docking station (Figure 2-10) for the IMSS vehicle supports three functions: battery recharging, radio and wire ethernet communication, and it provides a fixed location for registration of the vehicle with the building coordinate system.

The vehicle batteries are charged at a 60 amp rate using a 5 kW variable voltage DC power supply. The power supply requires 208 VAC, 3-phase building power. At a 60 amp rate the batteries can be charged to their full 95 amp-hr capacity in under 30 minutes. Power is supplied to the vehicle through two spring loaded contacts that mate with charge plates on the rear of the vehicle near floor level. The contacts are energized by a charge relay only after two safety interlocks are overridden. The first safety interlock is defeated only when the weight of the vehicle rear wheels depresses a spring loaded pedal under the wheels. The second safety interlock is defeated only when the vehicle has docked completely and has fully compressed the spring loaded charge contacts. A guard plate is located above the contacts to deter accidental depression.

The vehicle automatically recharges its batteries as needed. The vehicle will automatically delay the start of a mission or return in the middle of a mission to recharge batteries, and then resume the mission.

The docking station includes a small frame that contains three antennas used to communicate with the vehicle. This frame is mounted on the inside wall of the building at a height above the highest level of drums. One antenna is for the radio ethernet. Another antenna supports a remote control panel from which the vehicle can be signaled to "pause" its operations or to initiate an "emergency stop". The third antenna provides a live video feed from a camera on the vehicle monitor at the docking station, so that a casual visitor or somebody using the remote control panel can more easily observe and verify the operations of the vehicle.

2.5 Report Structure

The description of basic requirements, background material, and many fundamental design features are retained from the Phase 1 and 2 documentation, and have been updated to reflect the final vehicle design. 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 three sections. Section 5.1 summarizes the design upgrades performed during phase 3. Section 5.2 on "System Design" presents the system architecture and subsystem block diagram, and Section 5.3 discusses the specific upgrades performed on each subsystem in turn.
- Section 6, "Results and Discussion" presents the results of the field trial and installation process, including the operating conditions and structure of the facilities, the significant issues for the installation and operation at each facility, and performance results for the inspection process in the facility.
- Section 7, "Conclusions" summarizes the Phase 3 efforts and the associated performance results, and discusses lessons learned at each facility and uncovered issues that should be addressed in future efforts.

3. PURPOSE

The purpose of this effort was 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 developed 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 provided in the Phase 2 report (Appendix A) 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	<ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - design for contamination control
Safe operation in environment	<ul style="list-style-type: none"> - fail operational to ensure return to base and no collisions or runaways - non-sparking to avoid volatile combustion - bumper sensor for immediate stop on contact
Perform Mission Without Human Intervention	<ul style="list-style-type: none"> - Intelligent vehicle executive - map based planner - realtime sensor based control - sensor based replanning
Detect Anomalous Characteristics	<ul style="list-style-type: none"> - provide background measurement capabilities for volatiles and radiation - detect rust patches, dents, scratches
Log Locations and Characteristics of Anomalous Measurements	<ul style="list-style-type: none"> - provide data archiving on board vehicle - transmit to console at mission end - provide navigational measurements to locate events - archive visual information for anomalous events - provide bar code and label reading system
Characterize Nature of Contaminants for related investigations	<ul style="list-style-type: none"> - modular sensor suite for multiple instruments - be able to install instruments for detailed investigation of leaks (eg. spectrometers) - sample collection system
Provide Realtime Control and Feedback to Operators if Necessary	<ul style="list-style-type: none"> - allow direct operator control of all autoumous 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	<ul style="list-style-type: none"> - be able to operate on database to select and correlate desired information - automatically print out reports after inspection
Report Mission Status	<ul style="list-style-type: none"> - executive planner must record status of its tasks - auto print map and path
Accomodate Future Unknown Tasks	<ul style="list-style-type: none"> - modular interfaces for additional equipment (data, electrical, mechanical) - 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 3-2 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 were 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.
- Superficial rust (paint corrosion) - track diameter size; if rust is increasing, identify.
- Streaks of rust - identify source; if source is from outside and rust is superficial, ignore (water on drum top, leaking roofs, standing water); if source is from side of drum or under lid, identify.
- Non-superficial 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 were 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 opened 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 the 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 significantly reduce 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 an 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 more quickly (in terms of drums per week) allowing the sites to more easily comply with the RCRA regulations. The issue of integration of autonomous inspection and reporting functions into facilities operations to assist in RCRA compliance

must be pursued on a site-by-site basis as the regulatory agreements in place are often site-specific. The issue of RCRA and state regulatory compliance was pursued for the IMSS system with preliminary discussions occurring during the Phase 3 development effort. The concepts of autonomous inspection and reporting were positively received by regulators at this stage of development, although no specific involvement of the regulatory agencies was incorporated into this phase of the program.

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. The particular cost elements in this comparison were developed in conjunction with personnel at the facilities indicated in Section 4.1 (Oak Ridge National Laboratory, Hanford Engineering Laboratory, Idaho National Engineering Laboratory, and Rocky Flats Plant).

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 based on OSHA and RCRA training requirements gathered from DOE facilities for workers operating in a waster storage facility.

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 $52 * 72 = 3744$). Given these costs and productivity, an overall comparison is shown below:

manned - \$195 / hour

automated - \$56 / hour

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

4.2.2.5 Time

To verify the assumption of at least equal inspection time per 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 would undergo a decontamination process consistent with facility procedures for removing any equipment from a storage facility, specifically a radiation survey of the vehicle hardware and decontamination of any contaminated components. As the vehicle interior would have limited exposure to the facility environment (via filtered airflow), it is likely that only the detachable exterior vehicle covers would be affected. This evaluation is based on the experiences with the IMSS and ARIES systems at their respective deployment sites.

4.2.2.7 Institutional and Regulatory Goals

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

5. METHODOLOGY

This section outlines the design modifications made to the Phase 2 vehicle and associated systems to prepare for both the Fernald Field trial in May 1996 and the INEL site installation in April 1997. Because the fundamental design of the vehicle has remained unchanged from Phase 2, this section has a parallel structure to the Phase 2 report. In cases where no change has been made, the reader is referred to the Phase 2 report for the details. However, in cases where upgrades to the system design have been made, these changes are documented. For ease of reference, the Phase 2 report has been attached as Appendix A of this document.

5.1 Design Process

No modifications are necessary to this section.

5.2 System Overview

No modifications are necessary to this section.

5.3 Subsystem Designs

5.3.1 Mechanical Subsystems

5.3.1.1 Vehicle Structure

While the structure of the vehicle base remained the same from the Phase 2 vehicle, a fourth level mast extension was added to permit the inspection of the five high drum stacks at the INEL storage facility. Figure 5-1 shows the revised dimensions for the Phase 3 vehicle.

5.3.1.2 Motion Platform

No modifications are necessary to this section.

5.3.1.3 Sensor Mast and Sensor Suite

Construction of the fourth level sensor suite incorporated an aluminum mast segment of 42" with a new sensor suite and all associated inspection subsystems: a barcode reader, a laser and monochrome camera for GIS operation, and a pair of color cameras for COR acquisition and processing. The additional tilt axis was configured to operate using the spare channel on the Galil motion controller dedicated to tilt control. The mast extension itself is different from the lower levels in that it is a single 1/8" 4"x4" hollow aluminum unit, as opposed to a split configuration of the lower levels. This reduced the overall mast weight, and especially the moment applied to the base. This change required that the camera bodies and power distribution units be attached as a unit to the inside of the extension, allowing it to be easily slid in and out of the hollow mast extension, as there is no front access to this level.

The radio ethernet, telemetry, and video link antennas were placed on a new sliding mount attached to the mast. This mount allows for flexible positioning of the antenna height above the top mast segment for both three and four level configurations.

Figure 5-1. Diagrammatic Side View of Phase 3 Vehicle.

5.3.2 Electrical Subsystems

5.3.2.1 Vehicle Electronics

The fundamental configuration of the vehicle electronics was unchanged from the Phase 2 vehicle. The principal phase 3 modifications were upgrades to the system to incorporate new functionality needed for the INEL storage facility. The following changes were made:

- processor upgrade for color inspection subsystem
- installation of a radio telemetry module and remote keypad
- installation of live video link and mast camera
- addition of shutter control to the color camera subsystem
- installation of 2 GB disk
- installation of 4th mast segment (cabling, i/o, control cables, video)
- installation of pause switch electronics

These changes affected the vehicle electronics in the following ways.

The processor upgrade for color inspection exchanged the three Phase 2 COR processing motherboards including four C40 processing modules and two color framegrabbers operating at 40 MHz, for three new motherboards with ten C40 processing modules and two color framegrabbers operating at 50 MHz. This configuration allowed the addition of the ABCD processing software while maintaining inspection throughput.

The radio telemetry module and remote keypad were installed as a means to provide remote operation of the vehicle in the INEL facility via an analog radio link. The details of the operation of the telemetry module are presented in the operators manual (Appendix B--Section 8.2). The associated modifications in the vehicle electronics were the addition of connections to the emergency stop, pause, and reset circuitry of the vehicle from the telemetry module. The radio link operates at 218 MHz.

In order to simplify the process of monitoring the position and status of the vehicle in the INEL facility, a video link between the vehicle and the base station was created by installing an additional monochrome camera on the mast, attached to an analog 1.71 GHz transmitter communicating with a receiver located at the base station. There a monochrome video display can be attached to provide direct feedback on vehicle position. The only modification to the existing vehicle electronics was the cabling associated with providing power to the camera and video transmitter and a control line for controlling the camera power.

The addition of electronic shutter control to the camera system was essential for the variable lighting conditions found at both the Fernald and INEL storage sites. Each color camera can have the integration time (time which the CCD element is gathering light) controlled via three discrete digital inputs, providing three bits (or eight levels) of timing control. The required modification for the vehicle was the addition of control lines between the digital output of the main processor system and each camera sensor suite and the reconfiguration of the camera cabling to accept these control signals.

In order to increase the available image storage for the color vision system, a 2 GB SCSI disk was installed in the vehicle, replacing the existing 500 MB disk. There was no other modification to the vehicle electronics for this upgrade.

The addition of a fourth level mast extension required that power, control, and video lines be added to the vehicle electronics, in addition to the actual components used in the mast extension (tilt motor/encoder, barcode reader, laser and monochrome camera, and two color cameras). The actual control electronics in the vehicle base already existed based on the original vehicle design for adding a fourth level, including the necessary motion control lines and video inputs for inspection, so no electrical modifications were required in this regard.

Finally, a pair of switches and associated cabling to a discrete digital input on the main processor system was added to the vehicle to allow a "Pause" function to be added to the vehicle. This function is designed to allow the operator to temporarily suspend vehicle operation and re-enable it at a later time.

Based on the current vehicle state a new detailed control electronics diagram is presented in Figure 5-2.

Figure 5-2. Control Electronics Detail.

5.3.2.2 Ultrasonic Sensing

5.3.2.3 Communications

The on-board vehicle communications were unchanged from the Phase 2 vehicle; however, several additions were made to improve vehicle to base station communications. The first was the addition of the radio telemetry module on the vehicle which allows a user at the base station to issue simple vehicle commands via a keypad. The system operates via an 218 MHz analog radio link in the facility. The details of the system operation are provided in the IMSS Operator's Manual (Appendix B, Section 8.2). Additionally, a live video link was added between the vehicle and the base station. The purpose of this link is to allow a user to remotely monitor the vehicle via live video image of the current vehicle position. This was implemented with a 1.71 GHz analog video link, providing the video output of a monochrome camera on the vehicle mast at the base station, displayable on a monochrome video monitor. Finally, a socket-based messaging system was added to the vehicle-operator workstation system, allowing the vehicle to receive operator commands from the operator workstation and report current vehicle status to the operator workstation in a robust manner even while the vehicle is in the facility inspecting.

5.3.2.4 Power

The primary power subsystem, consisting of 40 NiCD battery cells remained the same as described for the Phase 2 vehicle. During Phase 3 the completed docking/charging station was integrated into vehicle operation. Figure 5-3 shows the configuration of this unit. The charging station power supply provides the batteries a 64 Volt / 60 Amp power source for charging when engaged. The battery charge cycle is approximately 25 minutes in this configuration. The 28 V secondary power sources used during Phase 2 development are no longer part of the vehicle system.

Figure 5-3. Vehicle Docking Station.

5.3.3 Safety System

All of the safety system components described in the Phase 2 report are still in place. In addition, safety interlocks were added to the system based on the integration of the charging station into vehicle operation. Specifically, a three part strategy is employed to guarantee operator safety. First, the vehicle must activate a switch located under the docking station ramp, requiring significant weight. Second, the vehicle must be located close enough to the charging contacts of the docking station to depress the spring loaded contacts sufficiently to engage a second switch. Finally, a Lexan shield is located above the activated charging plates to prevent accidental exposure.

A second addition to the safety subsystem was the creation of a "Pause" function which allows the operator to suspend vehicle operation (motion) temporarily to ensure that vehicle operation does not conflict with human activity in the facility. The function can be activated from either the vehicle, where either of two switches located on the vehicle can be used to enable/disable the Pause mode, or from the remote keypad at the docking station.

An additional red kill switch was added to the top front of the vehicle arm for easier access from the front of the vehicle. Also, two whisker-type contact sensors were added to the

sides of the mast at the height of the lowest level sensor suite to protect the sensor hardware.

5.3.4 Control

No modifications are necessary to this section.

5.3.5 Navigation Subsystem

The fundamental navigation subsystem is unchanged from the Phase 2 vehicle. However, a number of changes were incorporated to improve system robustness, based on experiences with the large facility structure at the Fernald site and in the DPF Facility at the Lockheed Martin site.

5.3.5.1 Dead Reckoning

The information from Phase 2 remains accurate. The number of dead reckoning was further reduced during Phase 3 development, with the addition of ultrasonic alignment for both vehicle docking and the vehicle movement between the docking station and the facility corridor.

5.3.5.2 Navigating Aisles

The information from the Phase 2 report remains accurate. The process of locating a drum within an aisle was made more robust. The ultrasonic-based drum finding system now compares measured drum position against *expected* drum position derived from facility model. Any large deviation is defined as a navigation sensing error, and vehicle will attempt twice to re-locate the drum again, and will abort that navigation command if none of the retries succeed. The process of re-locating the drum is for the vehicle to return to its last verified/known position (the previous drum) and perform the same drum-finding operation again.

An additional navigation operation was added to help the vehicle align itself within the aisle while inspecting the first and second drums. Because the pallet ultrasonics are not in position to properly align when the vehicle first enters the aisle, an initial step was included in the process of inspecting these drums. First, the vehicle must enter the aisle and go to the third drum, allowing the pallet-level ultrasonics to properly align the vehicle base with the aisle. Then, the vehicle returns to these drums for inspection with the alignment properly set.

5.3.5.3 Finding Aisles

The information from the Phase 2 report remains accurate.

5.3.5.4 Obstacle Avoidance

Several improvements were made to enhance the performance of the obstacle detection and avoidance subsystem. The obstacle detection task is now active at all times the vehicle is in motion. The mast ultrasonic sensors are now incorporated in the obstacle detection process with the vehicle navigation operations turning the mast to face the direction of motion to employ these sensors. Once an obstacle is detected, recovery code aborts the failed navigation command, moves the vehicle back to the last previously known position, retries the navigation command two times, and if the retries all fail then the navigation command will fail. When a navigation command fails, then the current "plan command" will fail and be aborted, and the vehicle will attempt to execute the next plan command in the mission plan. Typically, a plan command is to inspect one side of one row.

A second enhancement to further protect the vehicle was the addition of physical collision detection bumpers and switches to the mast in conjunction with the level one sensor suite. These *whiskers* provide an immediate E-Stop of the vehicle when they make contact with an obstacle. They are sufficiently sensitive and flexible to protect the mast sensor suites from damage from inadvertent vehicle motion. This coupled with the other ultrasonic and skin-based obstacle detection components provide an integrated solution to protecting the vehicle.

5.3.5.5 Docking / Undocking

A new aspect of the navigation subsystem for the Phase 3 vehicle was the addition of automated docking and undocking operations using the vehicle ultrasonics to accurately align the vehicle with the docking station. For docking the ultrasonic sensors are used both to align the vehicle with the docking station and determining the vehicle distance to the docked position.

Also part of the initial/final vehicle operation associated with undocking/docking is the traverse to the corridor entry point where the vehicle begins to use feature-based navigation. The Phase 2 vehicle used a series of dead reckoning moves to accomplish this. In the Phase 3 vehicle this dead reckoning traverse was reduced by using a wall following stage to align the vehicle with the row nearest the docking station. In this way the odometry errors that could potentially accumulate due to a long series of dead reckoning moves are reduced.

5.3.6 Mission Sensing Subsystems

5.3.6.1 Geometric Inspection System

No modifications are necessary to this section.

5.3.6.2 Color Vision System

The fundamental concept of the color vision system is the same as in Phase 2. The goal is the detection of visual anomalies of the drum surfaces in the form of rust, rust streaks, and other evidence of corrosion or leakage, using a pair of color cameras in the sensor suite opposite each drum level. The cameras are verged on the drum to provide views of the left and right sides of the drum, and the sensor suite tilt mechanism provides vertical coverage of the drum. Halogen lamps located above each camera provide additional illumination in low light conditions. The collected color images for each level, tilt, and side are sent to a set of parallel real time image processing boards in the form of red, green, and blue image bands. For each level one processor is dedicated to locating new regions of rust forming on the drum (the COR classifier) and another is dedicated to locating change between the current image and a baseline image of the same surface region acquired in the past. In this section, the Phase 3 activities relating to the upgrade of the processor architecture for color vision processing and the operation of the COR and ABCD processing tasks is detailed.

Processor Upgrade

As part of the INEL site installation the hardware and software in the color vision inspection subsystem was substantially modified. The principal hardware upgrade for the system was the modification of the processing architecture to dedicate processing hardware for each of the five levels of drums. This required the installation of a new TMS320C40 processor set and associated support hardware. Figure 5-4 shows the basic configuration of the new hardware. Three new Traquair HEV40-4 motherboards were purchased

(shown shaded in the figure). These provide four C40 processing module slots which were used to both acquire the color imagery (L and R in the figure) and process at each level (M# and S# for each level in the figure). The improvements over the Phase 2 configuration include the speed of the individual processors, operating now at 50 MHz versus the previous generation 40 MHz, the smaller footprint of each processor, the application of two processors for each level of drums, and the addition of processing for level four and five drums.

Figure 5-4. Color vision system processor architecture.

This architecture communicates with host processor across the VMEbus using a VxWorks/C40 messaging system in the same way as before; however, now in addition to the level one master processor having access to the host processor, the level two and four master processors do as well. This allows greater throughput for both image and messaging traffic necessary for the inspection tasks.

The principal software task in adapting to the new processor configuration was implementing a coordinated scheme for both image acquisition and processing sequencing. The framegrabbers are the limited resource for the image acquisition task. The resulting acquisition sequence then partitions the master processors into groups, first acquiring the first level images which are also used for aligning the vehicle, then acquiring the second and third level images, and finally the fourth and fifth level images. The third level sensor suite is used in acquiring both the third and fourth level drum images; first tilting down to acquire the third level set and then up to acquire the fourth level set.

The second principal software task during Phase 3 for color inspection was the porting of the Automated Baseline Change Detection (ABCD) software developed by Kinetic Sciences, Inc., from a Macintosh-based platform to the vehicle. This porting operation occurred in three phases. First, the ABCD phase 1 operation was tested with the vehicle performing only the image acquisition task, and the processing tasks occurring off line on a Macintosh platform. This testing occurred both at Astronautics, Denver and at the Fernald site. Then the ABCD code was ported from its Phase 1 configuration to the C programming language by Kinetic Sciences. The resulting code was then migrated to a UNIX platform and migrated to the vehicle. The constraints of both memory and processing time required modification of the original code set to allow sufficient throughput for the inspection task.

Shutter, or integration timing, control of the cameras was also added during Phase 3. This capability was necessary for the high variable lighting conditions present at both the Fernald site and the INEL site. As images are acquired by the cameras, the light level over a window in the center of the frame is computed, and the integration time (the time the CCD imager acquires light from the scene) is adjusted to be shorter or longer in order to make the image darker or lighter, respectively. This capability was added via the installation of three digital control lines for each sensor suite, providing three bits or eight levels of integration timing control.

COR Inspection Process

The corrosion (COR) inspection process operates by identifying regions of the drum surface which possess the color characteristics of rust. This characteristic is quantifiable based on the proportion of red, green, and blue components present at a given point on the drum surface and is dependent on the camera, lighting, and drum surface characteristics. A bayesian classifier is used to classify each pixel as rust or non-rust using a prototype of the rust class which is obtained for the current operating facility and light levels.

ABCD Inspection Process

The ABCD inspection process operates based on comparison of the current image of the drum surface with a baseline image of the same region, detecting change in appearance that could be due to the formation of corrosion features or leakage of the drum. When the vehicle makes its first inspection run for a segment of the building, it acquires and stores the four-image baseline image set for each drum. Figure 5-5 shows this image set. These images are stored on the hard disk drive on the vehicle. When the next, and later, inspection runs are performed on the same section of the facility, the vehicle performs a registered, normalized image differencing operation between the current inspection image of the drum surface and the stored baseline image. Figure 5-5b) shows this image set. Changes in appearance, quantified as changes in intensity between the baseline and inspection image constitute regions of interest flagged for operator review. The size of intensity change and the spatial extent of the image region which constitutes a *significant* change worthy of the operator's attention are variable and can be changed to adapt to the characteristics of the current operating environment.

a) baseline image set

b) inspection image set

Figure 5-5. ABCD images.

In order to guarantee that the vehicle is properly aligned in front of the drum, a fiducial label is placed on the drum surface. The vehicle aligns itself so that each time it visits a drum the fiducial is aligned at the same point in the image. This ensures that the comparison between the baseline image and inspection image is as reliable as possible. Figure 5-6 shows a fiducial label. Additionally, the gray scale present on between the two checkerboard fiducial markers provides a means to normalize the intensity level between the baseline and inspection images.

Figure 5-6. Fiducial label.

The steps involved in the ABCD inspection process are

1. Adjust vehicle position in front of drum using fiducial on level one,
2. Acquire inspection images for level one,
3. Acquire inspection images for level two and three,
4. Acquire inspection images for level four and five,
5. For the four quadrants of each level:
 - a. locate fiducial and extract grayscale
 - b. perform COR processing on slave processor
 - c. retrieve ABCD baseline image for quadrant
 - d. compare baseline and inspection images
6. For each level:
 - a. return any COR or ABCD defects
 - b. if defects are found, then return drum images for review with defects marked with box surrounding suspected defect

A diagram of the processing structure for the inspection sequence is shown in Figure 5-7.

Figure 5-7. Color Vision System Inspection Diagram for One Level.

5.3.6.3 Bar Code Scanner

The bar code scanning operation remains unchanged from Phase 2. However, due to the potential for bar codes to be placed at non-central locations of the drum surface an optional vehicle position adjustment operation was developed and used at the Fernald site. This approach augmented the standard bar code inspection by adjusting the vehicle position forward and back of the standard centered position if a bar code was not found on one of the levels. In this way more of the bar codes could be recovered at the cost of the additional time to move and perform a bar code read at the secondary positions.

5.3.7 Operator Interface

While the basic concept of the operator interface remained constant with respect to the Phase 2 design, a significant overhaul was performed on its operation. The most significant aspect of this upgrade was the port of the operator interface to a single standalone workstation (Sun SPARCstation 20) with display capabilities for both the interface and the associated defect image display. The display for the operator interface was improved in both operation and look and feel, and now provides the operator with direct feedback on the current vehicle status and allows the operator to command the vehicle inspection task directly. Also, a complete operators manual which covers the use of the operator workstation as well as the vehicle operation was created (Appendix B). The

specifics for each component of the operator interface are covered in the remainder of this subsection.

5.3.7.1 Facility Model

The basic structure of the facility model remains consistent from Phase 2. Additional abilities were added to work with the pallet and drum configurations found at the INEL site. Specifically, the INEL drum stacking configuration is based on rows which are four drums wide for 55-gallon drums and three drums wide for 85-gallon drums, with both stacked on a 4'x8' pallet. Thus, the facility model row class was expanded to include these potential stacking configurations as well as handling varying pallet size (54" vs. 48") often used for stacking 85-gallon drums.

5.3.7.2 Facility Model Editor

The facility model editor was completely revised from the Phase 2 version. The configuration of the new Facility Model Editor (FME) provides a simple visual interface adapted for ease of use in INEL facilities. A complete description of the operation of the FME is provided in the IMSS Operator's Manual (Appendix B--Section 7). The FME provides the operator with direct graphical control over all the variable configuration quantities in the INEL facilities including, row configuration, row position and dimensions, row alignment, central corridor dimensions, and docking station position. The generated facility map is used directly by the vehicle in performing inspection operations. Figure 5-8 provides a sample facility model generated by the FME.

Figure 5-8. Sample Facility Model.

5.3.7.3 Mission Assignment

The Mission Assignment screen allows the operator to select the portions of the facility that are to be inspected for the current mission. The mission assignment component of the operator interface was substantially upgraded from the Phase 2 version. The complete details on the operation of the mission assignment screen are provided in the IMSS Operator's Manual (Appendix B--Section 6.2). The most important improvement made for the operator is the simple/intuitive generation and editing of an inspection mission based on the INEL grid configuration.

5.3.7.4 Mission Assessment

The Mission Assessment screen allows an operator to review the inspection results of a mission. These results include a list of the defects that the IMSS vehicle detected as part of the selected inspection mission. This interface was also upgraded as part of the Phase 3 effort to improve the operator ease of use. The basic characteristics of the interface provide the operator with the ability to review and sort the defects found in the selected mission according to drum level, drum position, defect type, defect status, and date the defect was found. Additionally, the drum images associated with any defect found on that mission are presented to the operator. The complete details on the operation of the Mission Assessment screen are present in the IMSS Operator's Manual (Appendix B--Section 6.3).

5.3.8 Mission Executive

The principal improvements in the Mission Executive software for Phase 3 were in the automation of specific vehicle tasks and modifications for continuous operation of the vehicle from the operator interface. Once the vehicle is powered on, it performs an initial homing operation to test and align the motor axes on the vehicle, and then enters a waiting mode. The vehicle remains in this state until a new mission is downloaded from the operator workstation and executed. A new socket-based messaging system was developed for the communication link between the operator workstation and the vehicle, providing a robust means for both downloading and uploading inspection information and for the vehicle to provide its current status during inspection missions. The executive also handles the automated operation of the undocking and docking operations for the vehicle during missions.

A final important improvement is the addition of automated vehicle charge monitoring and the supporting tasks. This set of tasks constantly monitors the vehicle's state of charge both while waiting at the docking/charging station and during inspection operations. If the vehicle state of charge falls below 45 Volts, then a automatic recharge process is initiated. In the case the vehicle is at the docking station, this involves merely engaging the charge relay. However, in the case the vehicle is out in the facility, the current inspection operation is suspended and the vehicle returns to the docking station and then engages the charge relay. At 45 Volts sufficient power still remains to safely return to the docking station from anywhere in the facility. During the automated charging operation the vehicle's state of charge is also monitored and the charge relay is disabled at full charge (approximately 60 Volts).

5.4 Test Facilities

Phase 3 development and testing occurred at four different sites. Initially the same Denver facility that was used for Phase 2 operations was used for pre-field trial activities. The Fernald Environmental Management Project (FEMP) site was the location of the initial field trial during May and early June 1996. Returning from the Fernald site in June,

modifications and testing for the INEL installation were performed at a new building of the Lockheed Martin Denver site, the Design and Production facility (DPF). The final installation operation for the vehicle (and its current location) is at the Idaho National Engineering Laboratory. The characteristics of each of these sites will be presented in this section, along with the preparations necessary for vehicle operation, the equipment used to support vehicle operation, and the training and certification needed for the Lockheed Martin personnel on site for development and evaluation operations.

5.4.1 Fernald Site (TS-4 Structure)

5.4.1.1 Site Configuration

"The FEMP is located in southwestern Ohio approximately 17 miles northwest of downtown Cincinnati, Ohio and eight miles southwest of Hamilton, Ohio. The FEMP site comprises 1,050 acres and the former production area occupies approximately 136 acres in the center of the DOE property. During production operations beginning in 1952, processing consisted of foundry and chemical processes and metal forming to convert natural uranium ore concentrates and recoverable, recyclable residues into uranium metal and compounds. The primary function of the plant was production of metallic uranium fuel cores and uranium compounds for use in U.S. defense programs.

All production activities at the facility have ended. The facility is now a superfund site on the National Priority List (NPL) of sites for remediation. Current activities at the FEMP include waste management operations, remediation, decommissioning and decontamination, nuclear materials disposition, waste storage of low level radioactive waste, mixed waste and nuclear materials, and miscellaneous operations such as wastewater treatment" ...(excerpt from FEMP Drum Inspection Robotics Visitor's Handbook--Ken Belgrave). The physical configuration of the complete FEMP site is shown in Figure 5-9.

In the northwest corner of the site, several Tension Support (TS) structures were installed to temporarily house drums of low level mixed waste prior to shipment offsite. The TS-4 facility, housing a large collection of 55 and 85 gallon waste drums, was chosen as the site for the IMSS field trial operation. The stacking configuration for the drums in the facility was single 4'x4' wide pallets with either four 55 gallon drums or three 85 gallon drums stacked up to three levels high. The length of the rows vary between four pallets and ten pallets deep. The configuration of the TS-4 facility is shown in Figure 5-10.

Fernald Environmental Management Project

Figure 5-9. FEEMP Site configuration.

Figure 5-10. TS-4 configuration (North Half).

The TS-4 facility required only one modification to accommodate IMSS vehicle operation: the addition of a 208 Volt 3-phase power outlet to the docking station area at the center of the facility. No other facility modification was necessary for operation during the field trial activity. A radio ethernet connection to the remainder of the FEMP facility was installed; however, during the field trial network operation was limited to the TS-4 facility, including the workstations and the vehicle.

5.4.1.2 Vehicle and Supporting Equipment

The Fernald field trial served as a site for evaluating the IMSS vehicle in a standard operational environment and for adjusting the vehicle hardware and software to better accommodate this environment. For this reason a complete set of hardware and software diagnostic and development tools were taken to the TS-4 facility. Additionally, due to the extended duration of the test (six weeks), the complete set of vehicle spare components and general office-related supplies were taken. A general list of the components includes:

- IMSS Vehicle
- IMSS Charging Station
- Four Software Development Workstations
 - 2 Sun SPARCstation 1+ workstations
 - 1 Hewlett Packard 9000/700 workstation
 - 1 Silicon Graphics Indigo workstation
- Ethernet Hub for workstation interconnection
- Arlan 620 Radio Ethernet Transceiver
- Macintosh 7200/75 for ABCD work
- Macintosh laptop for vehicle diagnostic monitoring
- Laserwriter IINT
- Diagnostic Equipment
 - VME Card Cage
 - Video Monitor and cabling
 - Multimeter
 - Oscilloscope
 - Soldering Iron
 - Heat Gun
 - Tool Set (wrenches, screwdrivers, flashlight,...)
- Miscellaneous office supplies
- Spare Vehicle Components

5.4.1.3 Training/Certification/Operational Requirements

In order to perform the field trial activities in the TS-4 facility, several requirements had to be met by Lockheed Martin personnel. First, a complete physical was required for all site workers, including EKG, blood work, and chest x-ray. Also, an operational requirement of steel-toe working shoes and safety glasses was in place for all site workers in TS-4.

The training necessary for Lockheed Martin personnel consisted of

- GET (General Employee Training)
- OSHA Site Worker Training
- Rad Worker I Training and Practical

This training required approximately four working days to complete and was performed in the first week of the six week field trial exercise. This training also provided certification to escort untrained visitors to the TS-4 facility for temporary work.

5.4.2 Design to Process Facility (Denver)

During the development period from June 1996 to March 1997 a secondary facility, the Design and Production Facility (DPF) at the Lockheed Martin Denver site, was used to support large scale operation of the vehicle and testing modifications performed as part of the preparation for installation at the INEL site. This area permitted a facility configuration consistent with the INEL structure and of sufficient size, two sides with four rows on each side, to permit realistic testing of navigation operation over both extended distance and time.

5.4.3 INEL Radioactive Waste Management Complex (RWMC) Site

5.4.3.1 Site Configuration

The Radioactive Waste Management Complex has seven transuranic mixed waste storage buildings, of which two are currently in use. Both 55 and 83 gallon waste drums are housed in these facilities. The standard stacking configuration for the 55 gallon drums is two rows of four 55 gallon drums on an eight foot wide by four foot deep pallet. The five levels of drums are held in place using plastic alignment rings. The structure of the RWMC site is shown in Figure 5-11 and the layout of Building 628, where the vehicle was installed is shown in Figure 5-12.

Figure 5-11. The RWMC site.

Figure 5-12. Building 628 configuration.

Two modifications were required for vehicle operation in Building 628. The first was the installation of a 208 Volt 3-phase power outlet inside the building for docking/charging station operation. The second was the installation of an ethernet drop for connecting the vehicle ethernet to the main RWMC ethernet backbone, allowing vehicle communication with the operator workstation located at a remote building (658) at the RWMC.

5.4.3.2 Vehicle and Supporting Equipment

A reduced equipment set was taken to the RWMC site, as the goal was system installation with tuning of the inspection software operation to adjust to the facility lighting, and of the navigation software operation to adjust to the floor characteristics and the precise facility configuration. The equipment can be divided into two lists. First, the equipment delivered as part of the installation and transferred to the INEL site property management:

- IMSS Vehicle
- IMSS Charging Station
- IMSS Operator Workstation (Sun SPARCstation 20)
- Arlan 620 Radio Ethernet Transceiver
- Spare Vehicle Components
- IMSS Operator's Manual

The second set of equipment is support hardware used for diagnostic and development operations in Building 628:

- Sun SPARCstation IPC workstation
- Hewlett Packard 9000/700 workstation
- Ethernet Hub for workstation interconnection
- Macintosh laptop for vehicle diagnostic monitoring
- Support Equipment
 - VME Card Cage
 - Video Monitor and cabling
 - Multimeter
 - Soldering Iron
 - Tool Set (miscellaneous wrenches, screwdrivers, flashlight,...)

Only the first equipment set remains as part of the delivered IMSS system. Future development work must address the issues of software licensing for the development software both on the vehicle and for the operator workstation.

For additional development of the operator interface a license for the UIM/X user interface development tool from Black and White Software must be relicensed to the development site. For additional development of the vehicle software a development license for the vehicle operating system, VxWorks, must be purchased and renewed on a yearly basis with Wind River Systems. Additionally to perform software development with the Traquair image processing hardware used for the COR and GIS inspection systems, a license for the Traquair parallel C compiler, 3LTIC, is necessary.

5.4.3.3 Training/Certification/Operational Requirements

The training requirements for working in the Building 628 facility are fundamentally the same as those for the Fernald site and include

- RWMC Site Access Training
- OSHA Site Worker Training
- Rad Worker I Training and Practical

Only the RWMC Site Access Training was necessary for our engineers, as the other requirements were completed during the Fernald Field Trial in May 1996. No additional operational safety requirements were in place, except for the use of direct reading dosimetry to maintain a constant monitor on the dosage level for each person in the facility.

Installation efforts were conducted within the INEL established procedures and limits of Radiological Work Permit RWP-970040.

6. RESULTS AND DISCUSSION

This section presents the result of Phase 3 evaluations, including site testing and performance evaluations at the Denver, Fernald, and INEL sites. Overall system operation at each of the sites is discussed in Section 6.2.

6.1 Subsystem Evaluations and Performance

6.1.1 Mechanical Subsystems

6.1.1.1 Vehicle Structure

This observations from the Phase 2 report are unchanged with the stiffness and vibration requirements continuing to be met with the mast extension in place.

6.1.1.2 Motion Platform

The mechanical elements of the motion platform have experienced no significant problems. One adjustment in the right-front pulley assembly driving the meccanum wheel was necessary due to damage in shipping to the INEL site. However, this adjustment was minor and demonstrated that in place mechanical adjustments are possible with few complications.

6.1.1.3 Sensor Mast and Sensor Suites

The only point of note in the mechanical operation of the mast assembly is the stiffness of the mast cabling at low temperatures (below 40° F) encountered in the Building 628 facility at the INEL site. In this temperature range the stiffness of the cabling provides additional drag on mast movement and requires that the motion control software allow additional time to complete mast repositioning movements. With this adjustment the stiffness is no longer an issue.

6.1.2 Electrical Subsystems

6.1.2.1 Vehicle Electronics

The general performance of the vehicle electronics was satisfactory in the Fernald TS-4 facility and the Denver DPF facility. The only electronic failures found during operations in these facilities were

- 48 Volt to 5 Volt dc-dc power converter replaced (10/1996)
- Stressed ultrasonic electronics boards replaced (11/1996)
- Galil Board controlling mast positioning replaced (2/1997)
- Galil Board controlling tilt positioning replaced (3/1997)
- Sensor suite level 3 Pulnix color cameras replaced (3/1997)

The general sensitivity of the Galil boards has been well established and a spare Galil board which can replace any of the control axes is maintained as a spare unit. The dc-dc power converter, ultrasonic boards, and sensor suite level three cameras were replaced using the spare component sets and repair of the camera components was arranged.

The low temperature operation in the INEL Building 628 facility produced two specific temperature-related electronics failures found during the installation process:

- 2 GB vehicle SCSI disk
- Wheel power amps

The temperature range for these failures was below 40° F with the facility averaging between 30° and 40° F during the first ten days of the installation process. The solution for power amplifier operation in this temperature range was to maintain vehicle power on at all times which was the planned standard operating procedure for the vehicle once installed. The correction of the disk failure was immediately addressed using a 500 MB replacement disk for operation. The more general solution to this problem is the use of a ruggedized disk, capable of operating down to at least 0° F.

6.1.2.2 Ultrasonic Transducers

The ultrasonic sensor operation was satisfactory for both navigation and obstacle avoidance in all Phase 3 operations.

6.1.2.3 Communications

The primary communication links for vehicle operation are the radio ethernet link between the vehicle and the site ethernet, the site ethernet, the analog telemetry link, and the analog video link. The radio ethernet link encountered specific radio interference problems with the site portable voice communication system at Fernald, operated satisfactorily at the Denver DPF site, and had initial problems with an unknown cause of communication dropouts at the INEL site which was corrected by adjusting the bit transfer rate to a lower value (from peak 1350 Mbits/sec to 250 Mbits/sec) and confining the center frequency to a band about 922 MHz. The analog telemetry and video links experienced no problems at either the Denver DPF site or the INEL Building 628 site.

6.1.2.4 Power

The battery system provided excellent performance. The average charge cycle requires only 25 to 30 minutes from minimum charge to full charge. This charging operation can then be followed by continuous navigation and inspection operations of 3-4 hours on average. These statistics have been accumulated both in the field trial activities and at the Denver DPF site.

The only incident that temporarily compromised the power system was a failure in the seal on one of the NiCd battery cells. The repair operation consisted of removing the full battery set from the vehicle base (sliding out the full 40 cell block), exchanging the cell with one of the available spare cells, and replacing the battery set in the vehicle. The time for this operation was 3 hours and then required the system be discharged to 40 Volts and recharged. This is the only incident of any failure in the power system and has not been repeated.

6.1.3 Safety System

The safety system including the new safety interlock components for the charging station were validated in operation at each of the sites. No incidents which compromised operator or vehicle safety occurred during the Fernald field trial and INEL site installation activities. Vehicle contact with the drums in the facilities never occurred.

6.1.4 Control

6.1.4.1 Vehicle

No additional control issues were addressed in the Phase 3 evaluation for the vehicle as a whole.

6.1.4.2 Sensor Mast and Sensor Suites

The new control aspects of the mast and sensor suite configurations were the addition of the fourth level mast segment and sensor suite, the addition of electronic shutter control to all the sensor suites, and the addition of a remote video link camera to the mast. The operation of the fourth level mast segment was validated both prior to shipment at the Denver DPF site and at the Building 628 installation site, including the tilt commands required to control the camera positioning, bar code reading, and camera operation. All of these components operated well and consistent with the existing sensor suite set.

The control of the electronic shuttering added to each of the sensor suites was validated in testing at the Denver DPF site, establishing the hardware correctness of the discrete control lines and the software employed in adjusting the timing for each camera.

The control of the video link camera on the vehicle was evaluated at both the Denver DPF site and the INEL Building 628 site. There were no problems encountered in controlling the camera power through a discrete control in software and the video link performed reliably in testing with line-of-sight operation.

6.1.5 Navigation Subsystem

The navigation subsystem for the vehicle was tested extensively at all of the sites. The primary mode of evaluation was in normal vehicle operation, correcting any anomalies in performance as they appeared. The specific subsystem evaluations performed in the Denver DPF facility prior to INEL installation were the repeatability of large scale dead reckoning movements, minimum aisle width for vehicle operation, and variability in pallet orientation. The minimum aisle width for vehicle operation was found to be 32 inches in direct testing with the aisle widths in practice varying from 36 inches to 42 inches. The large scale dead-reckoning repeatability and pallet orientation tests will be presented as part of the Mixed Waste Focus Area (MWFA) test report for the evaluation of the IMSS and ARIES vehicles.

The primary mode navigation testing occurred over long duration runs lasting several hours in the Denver DPF facility with row configurations the same as the INEL Building 628 arrangements to ensure consistency. During these runs only minor anomalies were encountered and the navigation performance was robust with regard to both corridor and aisle navigation for inspection. The obstacle detection subsystem and its navigation response of retrying a motion sequence twice and then aborting the current plan segment operated properly under all conditions.

The docking and undocking navigation operations were tested and refined to match the configuration and operating conditions at each site. At the INEL site an adaptive docking distance mode was added to the navigation subsystem to ensure that the vehicle would consistently mate with the docking station for charging. The basic navigation operation was evaluated in both close proximity to the docking station and up to 10 rows distant with reliable behavior.

6.1.6 Mission Sensing Subsystems

6.1.6.1 Geometric Inspection System

The subsystem testing performed during the Phase 2 evaluation period provides an accurate evaluation of the GIS subsystem capabilities. No specific additional evaluations of the subsystem were performed as part of Phase 3 operations.

6.1.6.2 Color Vision System

The primary addition to the color vision system capabilities in the Phase 3 development and evaluation period was the integration of the Automated Baseline Change Detection (ABCD) subsystem to the suite of inspection tools. A systematic evaluation of the resolution and geometric capabilities for the COR rust detection was presented in the Phase 2 report (Appendix A, Section 6.16.2). An evaluation of the ABCD subsystem was performed as part of the Phase I ABCD development and on the vehicle as part of the MWFA Phase I testing prior to installation of the vehicle at the INEL site. An example of the components of the ABCD inspection are shown in Figure 6-1.

a) Baseline image set.

b) Inspection image set

c) Changes identified.

Figure 6-1. Example of ABCD input and results.

The specific ABCD testing centered on the contrasting objectives of detectability of defects added to the drum surface contrasted with need for a zero false-positive cases (detecting a defect that is not present). The free variables in this operation are the size of defects added, the position of the defect on the drum surface, and the difference in intensity of the defects contrasted with the background drum surface.

The tests were performed over multiple runs on a drum set, beginning with the baseline run which captures the initial image frames used in for comparison. In the following runs (one or more) on the same drum set, defects were added to the drum surface in varying position on the drum surface and with varying intensity relative to the drum surface color. A general set of results of the performance of the ABCD subsystem will be presented in conjunction with the MWFA Phase I testing of the IMSS and ARIES vehicles. Some observations on the ABCD subsystem performance are presented here prior to that evaluation. The minimum consistently detectable defect size was found to be 0.375 inches in diameter at the drum center. Over the angular surface of the drum this size increases to a value between 0.375 inches and 0.5 inches. This minimum detectability threshold is coarser than desired for ideal performance, where defects down to 0.25 inches over the drum surface are desired to be detectable.

The current performance is a tradeoff between the goal to have *no* false positives detected, as this places a greater burden on the operators who must review the defect images, and the goal to have *all* true positives detected, regardless of size, since defects as small as a pin hole can be a precursor to a leak in a drum. The control on rejecting false positive defects is the spatial extent of the detected change and the average intensity change of the change region. With the control thresholds set for this testing less than five percent of the drums exhibit false positive defects, principally due to lighting artifacts (specular reflections on the drum surface). This threshold was set by the Lockheed Martin engineering team as an initial attempt to present a standard mode of operation for the testing and data collection phase at INEL with the expectation that the threshold would be modified based on the results of this operational testing. The only note to add to this discussion is that the first two drums in a row have a higher percentage of false positives (~ 25%) detected due to small variations in vehicle position over multiple runs. This position repeatability issue is due to variation in the exit and entry characteristics of the lower level ultrasonic sensors used to align the vehicle with the pallet.

The second performance characteristic evaluated is the variation in intensity from the baseline drum surface intensity. This testing, performed as part of the overall evaluation, used the placement of gray scale fiducial labels on the drums. The gray scale level at which change is detected relative to the baseline surface intensity in that image/surface region defines the change required for change detection. Currently the threshold for this detection is set at 20 percent change in the normalized grayscale intensity, or about 40 intensity units relative to a baseline surface intensity of 200 units (range 0-255). The consistent performance of this normalized threshold was validated in this testing with the consistent detection of changes in baseline intensity in this range.

6.1.6.3 Bar Code Scanner

The bar code inspection process was initially tested as part of the Phase 2 evaluation and is presented in the Phase 2 report (Appendix A). In addition to this nominal evaluation of the bar code inspection process specific tests with the site specific bar code labeling were