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Automated Baseline Change Detection Phases 1 & 2

Final Report
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1. Executive Summary

The Automated Baseline Change Detection (ABCD) project is supported by the DOE Federal Energy Technology Center (FETC) as part of its ER&WM cross-cutting technology program in robotics.

The primary objective of this project is to apply robotic and optical sensor technology to the operational inspection of mixed toxic and radioactive waste stored in barrels, using Automated Baseline Change Detection (ABCD), based on image subtraction.

Absolute change detection is based on detecting any visible physical changes, regardless of cause, between a current inspection image of a barrel and an archived baseline image of the same barrel. Thus, in addition to rust, the ABCD system can also detect corrosion, leaks, dents, and bulges. The ABCD approach and method rely on precise camera positioning and repositioning relative to the barrel and on feature recognition in images.

The ABCD image processing software was installed on a robotic vehicle developed under a related DOE/FETC contract DE-AC21-92MC29112 "Intelligent Mobile Sensor System" (IMSS) and integrated with the electronics and software. This vehicle was designed especially to navigate in DOE Waste Storage Facilities.

Initial system testing was performed at Fernald in June 1996. After some further development and more extensive integration the prototype integrated system was installed and tested at the Radioactive Waste Management Facility (RWMC) at INEEL beginning in April 1997 through the present (November 1997).

The integrated system, composed of ABCD imaging software and IMSS mobility base, is called MISS EVE (Mobile Intelligent Sensor System - Environmental Validation Expert). Evaluation of the integrated system in RWMC Building 628, containing approximately 10,000 drums, demonstrated an easy to use system with the ability to properly navigate through the facility, image all the defined drums, and process the results into a report delivered to the operator on a GUI interface and on hard copy. Further work is needed to make the brassboard system more operationally robust.

2. Introduction

This report documents basic requirements and background material for the DOE drum inspection problem, and describes the design upgrades and integration of the ABCD system onto the IMSS vehicle from their starting points in phase 1. The description of basic requirements, background material, and many fundamental design features of the two original system are retained from the Phase 1 documentation, and have been updated to reflect the final imaging/vehicle design.

This report focuses on the integrated system performance as opposed to the development of the subsystems in their respective earlier phases. Appendix A "ABCD Image Processing", doucments the detailed technical development of the ABCD improvements necessary to achieve the desired performance when integrated on the IMSS.

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 two sections. Section 5.1 summarizes the scope of work at the task level. Section 5.2 on "Technical Approach" presents the overall approach toward integrating the two major components, the ABCD Imaging System and the IMSS Mobility System.
- Section 6, "Results and Discussion" presents the results of parametric analysis of the ABCD system installed on the IMSS vehicle with its cameras and computers, and presents the results of the field trials and site 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 2 efforts and the associated performance results, and discusses lessons learned and uncovered issues that should be addressed in future efforts.

3. Purpose

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

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

Representative EPA and DOE approved inspection procedures from Hanford and Rocky Flats are presented and discussed in the next section. From these requirements, and from discussions with waste operations personnel at four DOE sites (Oak Ridge National Laboratory, Hanford Engineering Laboratory, Idaho National Engineering Laboratory, and Rocky Flats Plant), the functional requirements shown in Table 3-1 were developed during Phase 1.

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 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.

4. Background

4.1 Inspection Procedures

Representative EPA and DOE approved inspection procedures are shown in Appendix B, "IMSS Mobility System," as obtained 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), functional requirements were developed during Phase 1 (See IMSS Phase 1 Topical Report or IMSS Phase 2 Topical Report). A summary discussion of these requirements and procedures occurs below. It is noted that few specifics are provided in DOE documentation and consistency between sites is not maintained.

Most storage facilities have drums stored four to a pallet and have pallets stored in single rows. Stacking heights varied from two to five drums with an average of three. Aisle widths varied from 26" to 36". Aisle lengths varied from 20 feet to hundreds of feet. In general, space was left between the last pallet in a row and the adjacent wall. Positive inspection of each drum is required. Operator response to flagged drums is required within 24 hours. All drums must be inspected every six days.

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

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

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

From these rules and guidelines the following drum inspection requirements were incorporated:

- Locate and read barcodes to positively identify drums. Report if barcode is missing.
- Visual anomalies to detect and classify:
    - dents over one inch deep,
    - tilted drums,
    - missing or defective barcodes,
    - rust and corrosion.

- Types of corrosion to identify and parameters to record:
  - rust (surface area),
  - rust streaks (length),
  - corrosion (blistering, chipped, peeling, or missing paint) (surface area).
- Coloring of drums includes:
  - white,
  - gray,
  - black,
  - yellow, and
  - silver.
- Visual anomalies NOT to be flagged include:
  - accumulations of dust or dirt on ridges, rims, or seams;
  - condensation streaks of dust or dirt; and
  - symbols or other labels that are not barcodes.

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

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

4.2 Comparison of Stored Waste Monitoring Techniques

4.2.1 Current Stored Waste Monitoring Techniques

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

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

4.2.2 Advantages of Proposed Solution

4.2.2.1 Public and Occupational Health Risks

A major advantage is the reduced human exposure afforded by this system. Inspectors no longer need to enter the building to monitor the stored waste. The extended exposures during normal inspection add up quickly given the required frequency and total number of stored waste containers. Thus, using this autonomous system will eliminate the occupational health risks associated with this activity. This is even more important in the event of a discovery of a leak, or of collapsing drums which have inestimable costs in possible long term injuries. In fact, in the event of a leak, an autonomous system, equipped with a manipulator with advanced impedance control and contact stability algorithms, can use a siphon tool and bung puller to remove the material before removing the drum without risking breaking open full containers during transit.

4.2.2.2 Environmental Risks

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

4.2.2.3 Operations

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

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

4.2.2.4 Cost

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

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

- One full time inspection team (two inspectors) costs $150k / year including costs for wages, overhead (suits, sensors, *etc.*), support (exit exam and decontamination, *etc.*), and training.
- Use of time during an 8 hour shift includes 4 hours for inspection, 1 hour for preparation and transit, and 3 hours per day for reporting.
- Inspectors require 16 hours training per month (on average) or 4 hours per week.

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

- Cost of mobile sensor system after initial prototype is $200k / vehicle.
- Vehicle operates 8 hours on, 4 hours recharge per shift, 2 shifts per day.
- Vehicles do <u>not</u> operate on weekends.

- Required support is 30 minutes per trip for task loading and report generation by a human operator; 8 hours per week maintenance (nonproductive time plus labor charge), installation support of $10k per room (beacons and map generation).

Given these assumptions, calculated costs per year for the two different methods are as follows: manned - $150k / year and automated - $210k / year. The calculated productivity for each system in terms of hours of inspection time are: manned 768 hours / year (52 weeks - 2 weeks vacation - 2 weeks holidays = 48 weeks per year. Weekly productivity is 4 hours / day * 5 days / week - 4 hours / week training = 16 hours / week. Total productivity is 48 * 16 = 768) and automated 3744 hours per year (52 weeks per year; weekly 16 hours / day * 5 days - 8 hours maintenance = 72 hours / week. Total productivity is 52 * 74 = 3744). Given these costs and productivity, an overall comparison is shown below:

manned - $195 / hour
automated - $56 / hour

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

4.2.2.5 Time

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

4.2.2.6 Waste Minimization

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

4.2.2.7 Institutional and Regulatory Goals

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

5. Methodology

5.1 Tasks

The objective of this effort was to apply robotic and optical sensor technology to the operational inspection of mixed toxic and radioactive waste stored in barrels.

The Phase 2 scope of work was to produce and operationally test a freely autonomous waste barrel inspection at a DOE site. The Phase 2 mobile field system integrated the ABCD sensor with an autonomous mobile platform in a manner which satisfies DOE operational and regulatory requirements for automated waste barrel inspection.

Three tasks were performed under the Phase 2 contract as listed below:

TASK 7. INFORMATION REQUIRED FOR THE NATIONAL ENVIRONMENTAL POLICY ACT

The contractor shall prepare a draft report which provides the environmental information described in Attachment A2, "Required Information for the National Environmental Policy Act (NEPA)". This information will be used by the DOE to prepare the appropriate level of NEPA documentation for Phase 2 of the project. This draft report shall be submitted to the COR within sixty (60) days after contract award. DOE shall review the report and advise the contractor of the acceptability of the report or the need for additional information within thirty (30) days. The contractor shall submit a final report within two weeks of notice of acceptability of the draft report.

Until the NEPA review and approval process is completed the contractor shall take no action that would have an adverse impact on the environment or limit the choice of reasonable alternatives to the proposed action. The contractor is not precluded from planning, developing preliminary design, or performing other work necessary to support an application for Federal, State, or local permits.

TASK 8. FIELD TEST AND EVALUATION

The contractor shall build and integrate a field system prototype of the Change-Detection System to include an operational test and evaluation of an autonomous full function system at a DOE site. Prior to proceeding with this task however, the contractor shall prepare a test plan and forward it to DOE for review and comment.

TASK 9. PROJECT MANAGEMENT

The contractor shall manage the cost, schedule and technical elements of the Phase 2 effort. This task shall include project planning, oversight and reporting to the government, including subcontract management, if applicable.

The contractor shall prepare and submit reports in accordance with the Reporting Requirements Checklist and as applicable and described (in the original contract) in the Section D, DELIVERABLES. The contractor shall prepare and present briefings to the DOE as applicable and described in Section E, BRIEFINGS.

5.2 Technical Approach

The approach for phase 2 was twofold. First, we used the IMSS robotic vehicle developed at LMA in Denver as the positioning system for ABCD. This took advantage of related DOE development work and allowed this project to avoid duplicating costs. Second, we had to modify the ABCD imaging software to run on this platform. This effort, performed by Kinetics Sciences Inc., focused mainly on porting the software to run on real-time DSPs with limited memory and limited disk access (as opposed to the workstation environment it was originally developed in). The activity required to integrate and mount the system on the robotic vehicle is included as Appendix B - IMSS Mobility Platform. The activity required to port the software is included as Appendix A - ABCD Image Processing. These two self contained documents are from the engineering groups performing the work.

Parameterized System testing was performed at Denver in their mockup waste facility to extract system level performance measures across a wide range of possible cases. This was important because each different DOE waste storage site is internally fairly consistent, but different from the other sites. This made sure that final system testing was not biased toward one particular site. This testing is also discussed in Appendix B.

After completing final system integration and test, the (integrated) MISS EVE system was installed in building 628 at the RWMC at the INEEL. This included delivering the vehicle, reassembling it, connecting it to the network, performing some functional testing, and training some engineers at INEEL to operate the system. This installation is further discussed in Appendix B. Results are summarized in Sections 6 and 7 of this report.

6. Results and Discussion

The discussion of results in this section are limited to performance of the integrated imaging/ positioning system, specifically: (1) imaging performance of the integrated ABCD/IMSS system and (2) operational evaluation of the integrated system. Details on performance of the individual systems (e.g. the imaging system by itself or vehicle by itself) are covered by the appropriate reports in appendices A and B.

6.1 ABCD/IMSS Integrated Imaging Performance

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). 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.

6.2 Operational Evaluation

The IMSS system was deployed first at the Fernald TS-4 facility for field trial evaluation and after a development cycle at the Denver DPF facility was installed and currently resides at the INEEL Building 628 facility. As part of the evaluation process for determining vehicle performance a log book was maintained for recording vehicle operation. This log records data relevant to vehicle operation, including timing, power (voltages), and any anomalous behaviour encountered during the run. In this section, data from the logs will be presented in the form of operational statistics and significant events/observations about the facility and vehicle in the evaluation process.

6.2.1 Fernald Site--TS-4 Facility

The field trial activity at the TS-4 facility ran from May 6, 1996 to June 12, 1996. The first week of the time was spent completing the training requirements for unescorted access to the facility, unpacking and setting up the vehicle and computer equipment in the test area, and evaluating the working conditions, as TS-4 is a tent facility with some exposure to the elements.

Beginning in the second week an operational log was maintained to provide insight into the daily activities with the vehicle on site and establish statistics regarding the operational characteristics of the vehicle at this stage of development. The type of statistics that are of interest are the amount of time per day the vehicle is operating, the average time required for charging, the time spent on runs, and how these statistics changed over the course of the field trial.

During the course of the field trial the vehicle was directly running navigation or inspection missions over 31 hours with the average vehicle operation time per day approximately two hours with the balance of the time spent in vehicle adjustments (both hardware and software) which incorporated vehicle activity but were not documented missions. During the final week of operation the average mission time per day increased to over 3 1/2 hours as the vehicle operations became concentrated on mission operations. This improvement is also seen in the duration of the individual missions. The average mission duration increased from the early week times of 10-15 minutes spent evaluating exercising specific navigation and inspection tasks to over 30 minutes during the final week of the field trial. The maximum mission duration was almost 2 1/2 hours.

The only vehicle down time during the field trial was two days in the second week when the seal on one of the NiCd battery cells failed and the cell had to be replaced. The actual replacement operation required approximately three hours; the additional time was required to receive the cell from the Denver facility and properly discharge and recharge the complete battery system to assure consistent operation of the new cell.

An important feature of the TS-4 structure was the size of the facility, allowing the vehicle to visit over 23 rows on both sides of the north section of the building. During the course of the field trial the vehicle visited the majority of rows in this section of the facility and demonstrated navigation to and from the farthest row in this section. The number of rows visited or revisited during the field trial numbers more than 350. Additionally, the vehicle was able to navigate to the south side of the facility demonstrating both the operation of the vehicle using the ramps connecting the two sections of the TS-4 structure and long dead reckoning navigation operations.

Two specific missions to the east and west section of the test area were defined to demonstrate vehicle operation for the formal demonstration activity on June 12. These missions visited five rows on either side of the facility and inspected a selected subset of drum stacks. The timing of the missions was designed to require approximately 1/2 hour for each and provide observers with a clear view of the vehicle for explaining navigation and inspection operations.

The reported radiological dosage for the complete field trial activity varied among individuals with a minimum of 0 mRem and a maximum of 12 mRem. This dose level could easily be attributed to background radiation given an accumulated exposure time of six weeks.

6.2.2 INEEL Site--Building 628

The final stage of vehicle evaluation was the installation of the vehicle at the INEEL site. The initial phase of the installation process occurred over a two week time span in April 1997. The principal tasks during this activity were

- vehicle and docking station setup in Building 628
- attachment of fourth level mast extension and evaluation of performance
- operator workstation setup in Building 658
- evaluating general vehicle operation
- evaluating radio ethernet operation between vehicle and ethernet hub
- validating cross facility ethernet connection for remote operation
- validating remote operation--mission assignment, execution, and assessment

These tasks were completed during the two week installation process. During the course of this work several problems were identified and addressed. The principal environmental issue affecting vehicle operation was the low ambient temperature in the Building 628 facility. The mean operating temperature during the first week fell between 30° and 40° F during the work day. This resulted in the direct failure of the vehicle's 2 GB SCSI disk drive and inconsistent operation of the power amplifiers driving the vehicle wheels. The disk problem was corrected using a spare 500 MB SCSI disk with lower temperature sensitivity. The inconsistent power amplifier operation was addressed by maintaining continuous power to the vehicle electronics. As this is the planned standard operating mode, this was an acceptable arrangement.

The principal communication issue addressed in the installation process was the reliable operation of the radio ethernet system. The difficulty encountered was inconsistent dropouts in vehicle communication with the ethernet hub, resulting from an unknown source of interference. No specific source was identified in a spectrum analysis of the facility while the system was operating. As a result of this analysis, the corrective action taken was to reduce the transmission bit rate from 1350 Mbit/sec to 250 Mbit/sec and restrict the range of the transmission spectrum around the center operating frequency (922 MHz). The initial testing of this arrangement showed no problem in the vehicle-host link during a standard baseline inspection run; however, additional testing of this approach is necessary to validate it as a complete robust solution.

The radiation exposure level at the INEEL Building 628 facility was significantly higher than the Fernald site. Using the most reliable dosimetry available, the dose level averaged 1 mRem / hour working in the facility in the vicinity of the vehicle docking station with high dose levels possible working in the drum stacks. One anomaly that was encountered during the installation work was the incorrect reading of the initial direct reading dosimetry due to electro-magnetic interference from the radio ethernet system. The effect of working in close proximity with the radio ethernet antenna was a radically higher measured dose from the dosimetry. This effect was documented on several occasions and resulted in the change of dosimetry to the FastTrack monitoring system which is immune to this interference.

A dosimeter was attached to the vehicle to measure cumulative avoided radiation exposure. The dosimeter has not been read at this time, but it will provide an objective measure of the improved worker safety vis a vis avoided inspector exposure to radiation.

7. Conclusions

The performance of the installed system met engineering expectations. From a systems point of view, all functions (navigation and inspection) are performing as desired, and the system has the potential of saving a lot of costs ($150k/yr. per building) and of avoiding a lot of radiation exposure to inspectors. There are, however, two tasks that need to be performed before the system can truly become operational.

First, the Inspection Parameters must be validated from the inspectors points of view, leading toward approval by EPA for operational use. Testing is in progress to gather data, funded by EM-50 and the RWMC. While it has been verified that the inspection systems are functioning correctly, operators may want the results presented in a different way, may want the results to include some other additional information, may want the ratio of false positives / false negatives to be adjusted, or some similar change in parameters or reporting data. This should fall out from the current testing, and the MISS EVE inspection/reporting parameters can be modified at a later point in time.

Second, the hardware system must complete the transition from a 'brassboard' quality system to a manufacturing quality prototype. This would be accomplished by making a second system with all preceding patches incorporated into the manufactured design, much like the second unit of the ARIES project. The magnitude of this effort over and above the simple manufacture of a duplicate copy is fairly small. The desired changes would be an updated cabling harness for the mast, and the re-specification of some electronic components to handle greater temperature extremes.

8. List of Acronyms and Abbreviations

ABCD	Automated Baseline Change Detection
ARIES	South Carolina Inspection Vehicle
COR	Contracting Officer's Representative
DOE	Department of Energy
DPF	Design and Production Facility
DSP	Digital Signal Processor
EPA	Environmental Protection Agency
ER&WM	Environmental Remediation and Waste Management
F	Fahrenheit
FETC	Federal Energy Technology Center
GB	Giga Bytes
GUI	Graphic User Interface
IMSS	Intelligent Mobile Sensor System
INEEL	Idaho National Engineering and Environmental Center
KSI	Kinetic Sciences, Incorporated
LMA	Lockheed Martin Astronautics
LMMS	Lockheed Martin Missiles and Space
Mbit/sec	Mega bits per second
MB	Mega Bytes
MHz	Mega Hertz
MISS EVE	Mobile Intelligent Sensor System - Environmental Validation Expert
mRem	milli Radiation-equivalent measures
MWFA	Mixed Waste Focus Area
NEPA	National Environmental Policy Act
OTD	Office of Technology Development
R&D	Research and Development
RCRA	Resource Conservation and Recovery Act
RWMC	Radioactive Waste Management Complex
SCSI	Small Computer System Interconnect
TS-4	Temporary Structure 4

Appendix A

Automated Baseline Change Detection Image Processing

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AUTOMATED BASELINE CHANGE DETECTION (ABCD)

PHASE 2 FINAL REPORT

28 APRIL, 1997

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EXECUTIVE SUMMARY

Background

This document summarizes KSI's role in ABCD Phase 2, performed under P.O. # SBPDZ1730F and # SCAWG8701F.

The objective of Automated Baseline Change Detection (ABCD) is to automatically inspect hazardous waste drums stored in a warehouse, and identify any visual clues that indicate potential physical deterioration of the drums. By performing this drum inspection on board an autonomous mobile robot, unnecessary human exposure to hazardous environments can be significantly reduced.

Phase 1 of the ABCD project established, through analysis and demonstration, the viability of ABCD technology to the DOE waste management operational environment. This document describes the results of the Phase 2 tasks.

Phase 2 Objectives

The overall objective of Phase 2 is to integrate the ABCD system with the LM Astronautics (LMA, Denver) Intelligent Mobile Sensor System (IMSS) for implementation as MISS EVE (Mobile Intelligent Sensor System—Environmental Validation Expert) at the DOE Idaho National Engineering Laboratory (INEL). More specifically, KSI's main role is to implement the ABCD software as portable code written in ANSI C, and work with the LMA team to ensure that the software is successfully integrated onto MISS EVE.

Phase 2 Accomplishments

The ABCD project met all of its Phase 2 objectives. In Task 1, the ABCD software was ported and re-implemented in ANSI C. In Task 2, the ABCD software was successfully integrated into the operational software on board MISS EVE. Finally, as part of Task 3, magnetic drum labels were produced for the endurance trials at LMA (Denver) and for installation at INEL.

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1. FORMAL OBJECTIVES

1.1 Statement of Work

1.1.1 Objective

The objective of this effort is to apply robotic and machine vision technology to the operational inspection of mixed toxic and radioactive waste stored in barrels.

1.1.2 Scope of Work

This work, ABCD Phase 2, builds upon the work performed in Phase 1 (completed in February 1996). Phase 1 established, through analysis and demonstration, the viability of the ABCD technology to the DOE waste management operational environment. Phase 2 shall integrate the ABCD system with the LM Astronautics (LMA, Denver) Intelligent Mobile Sensor System (IMSS) for implementation in the MISS EVE (Mobile Intelligent Sensor System—Environmental Validation Expert) at the DOE Idaho National Engineering Laboratory (INEL).

1.1.3 Tasks to be Performed

Task 1: Port ABCD Phase 1 code to C

In this task KSI will implement in C code the algorithms that were developed in ABCD Phase 1 using IPLab. This consists of three main parts: fiducial location (for improved vehicle centering); image preparation (common processing required before storing a baseline image or comparing an inspection image), and change detection (comparison of baseline and inspection images). This code will be implemented according to interface and coding standards provided by LMA (Denver). Where feasible, KSI will develop this code in a fashion that will help ease future integration with the ARIES platform. Some assistance with this coding task is to be provided by LMMS (ATC, Palo Alto).

Task 2: Installation and Testing on MISS EVE

KSI will assist with integration of the code developed in Task 1 onto the MISS EVE platform. KSI will also assist with the testing of this code during the endurance trials at LMA (Denver) and during installation at INEL. This task includes travels as follows:

1. 3 days, RWMC facility inspection and integration design meeting, INEL
2. 4 days, Integration on MISS EVE, LMA (Denver)
3. 7 days, Installation testing, INEL

Task 3: Documentation & Labels

KSI will prepare appropriate documentation of the code developed in Task 1. KSI will also design and print the special drum labels necessary for the endurance testing at LMA (Denver) and installation at INEL.

1.2 Project Objective and Task Descriptions

1.2.1 Objective

The objective of this contract is to apply robotic and machine vision technology to the operational inspection of mixed toxic and radioactive waste stored in barrels, using automated baseline changed detection (ABCD) based on image subtraction. The objectives of each task are broken down as follows:

Task 1: Implement in C code the algorithms that were developed during ABCD Phase 1.

Task 2: Ensure the smooth integration and testing of the code developed in Task 1 onto the MISS EVE platform.

Task 3: Produce appropriate documentation of the code developed in Task 1. Also produce special drum labels necessary for the endurance trials at LMA (Denver) and installation at INEL.

1.2.2 Phase 2 WBS Listing

1. Port ABCD Phase 1 code to C
2. Installation and Testing on MISS EVE
3. Documentation & Labels

2. MAJOR MILESTONE STATUS

Task	Primary Task Description	Status
1.	Port ABCD Phase 1 code to C	Completed
2.	Installation and Testing on MISS EVE	Completed
3.	Documentation & Labels	Completed

3. CHRONOLOGICAL LISTING OF SIGNIFICANT EVENTS AND ACCOMPLISHMENTS

Significant Events

Date	Description
09/24/96	KSI delivers preliminary specifications (C function prototypes) for ABCD code to LMA team.
10/09/96	KSI trip to LMA to assist with ABCD integration onto MISS EVE (3 days).
03/03/97	Start of MISS EVE endurance testing at LMA.
03/12/96	KSI trip to LMA to assist with endurance testing.

Accomplishments To Date

Date	Description
09/30/96	First version of ABCD code delivered to LMA team (via ftp).
10/09/96	100 adhesive-paper drum labels delivered to LMA team for testing.
11/28/96	2500 magnetic drum labels delivered to LMA team for endurance trials at LMA and installation at INEL.
11/01/96	Final version of ABCD code delivered to LMA team.

4. ACCOMPLISHMENTS (BY WBS)

Task 1: Port ABCD Phase 1 code to C

The ABCD software was successfully ported and implemented in ANSI C, and the ABCD code was successfully compiled and tested on various platforms: SGI IRIX, SCO UNIX, SunOS, and VxWorks (running on MISS EVE's on-board DSPs).

Task 2: Installation and Testing on MISS EVE

KSI assisted the LMA team in successfully integrating the ABCD system into the VxWorks environment on MISS EVE. Topics addressed included timing and synchronization issues, and the allocation of computing resources to ABCD processing. Minor modifications to the ABCD code were made as needed by the LMA team.

Task 3: Documentation & Labels

ABCD algorithms, implementation details, and performance considerations have been documented in the ABCD source code and in this document.

2500 magnetic drum labels were produced for use in endurance trials at LMA and for installation at INEL. The drum labels are durable, easy to apply, and can be repositioned if needed. These labels enable the ABCD system to compensate for changes in image intensity over different images of the same drum. They also assist the IMSS navigation with positioning of the on-board cameras in front of a stack of drums.

5. TECHNICAL PROGRESS SUMMARY

This section describes the various components of the ABCD system, and shows how they were implemented in Phase 2. For background information and a more general overview, please refer to the ABCD Phase 1 Topical Report.

5.1 Drum Labels

The ABCD drum label (or "fiducial label") used in Phase 2 is illustrated in Figure 1. The "checkerboard" patterns enable the label to be easily located in an image. The other five squares provide reference greyscales for intensity normalization, to compensate for variations in illumination conditions over different images of the same drum. The ABCD drum label also assists the IMSS navigation with positioning its cameras in front of the stack of drums.

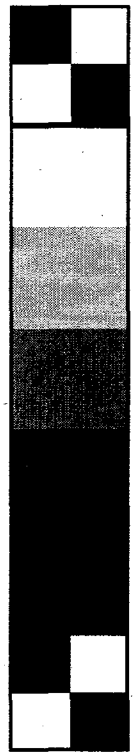


Figure 1: ABCD drum label

The drum labels produced for Phase 2 were made from vinyl with a magnetic backing. A dull surface texture minimizes specular reflections. This use of magnetic labels (first proposed by Peter Berardo, LMMS) contrasts with the use of adhesive-paper labels during testing in Phase 1. From an operational perspective, these labels have several important attributes:

- Durable
- Easy to apply
- Easy to remove (can be repositioned)

5.2 Overview of ABCD Algorithms and Code

During Phase 1, the core algorithms of the ABCD system were prototyped on the Macintosh using IPLab (image processing package) with some algorithms implemented in C as IPLab run-time libraries. In Phase 2, the ABCD software was implemented as a library of stand-alone functions, written in ANSI C for portability. All the functionality of the Phase 1 prototype was retained, but in some cases, features were disabled on board MISS EVE due to hardware limitations. These issues are described in the sections that follow and are also discussed in Section 5.10.

The diagram in Figure 2 shows the five main processing stages of ABCD:

1. At the Image Preparation stage, the location and grey scales of the drum label are recorded for each image. In addition, a "specular mask" is built for each image in order to mask out specular reflections.
2. The pixel intensities in the inspection image are then normalized in order to compensate for slight variations in illumination conditions between baseline and inspection images.
3. The two images are registered in order to compensate for variations in camera position.
4. The registered images are subtracted.
5. Finally, significant regions in the subtraction image are segmented and tagged during Blob Extraction.

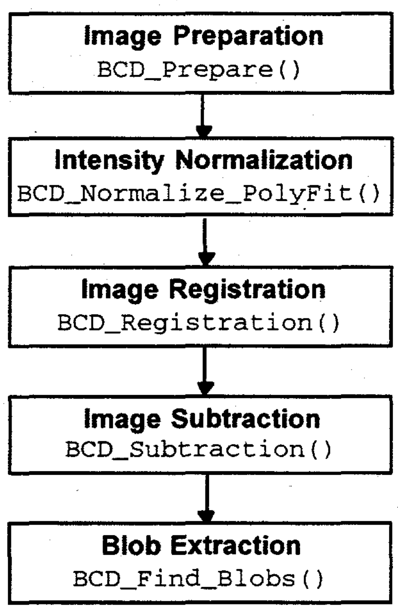


Figure 2: Stages of ABCD processing

Figure 2 also indicates the main code modules in which the ABCD processing occurs. The sections that follow describe each of these code modules in more detail. For detailed documentation on individual code modules, please refer to documentation contained in the source code.

5.3 Image Preparation

During the Image Preparation stage of ABCD processing, the drum label is located in the image, the greyscales of the label are sampled, and a specular mask is constructed. The purpose of the specular mask is to mask out any specular reflections appearing in the image that were caused by vehicle lighting. These masked-out areas are then ignored in the later stages of image registration and subtraction. Figure 3 shows the main code modules involved.

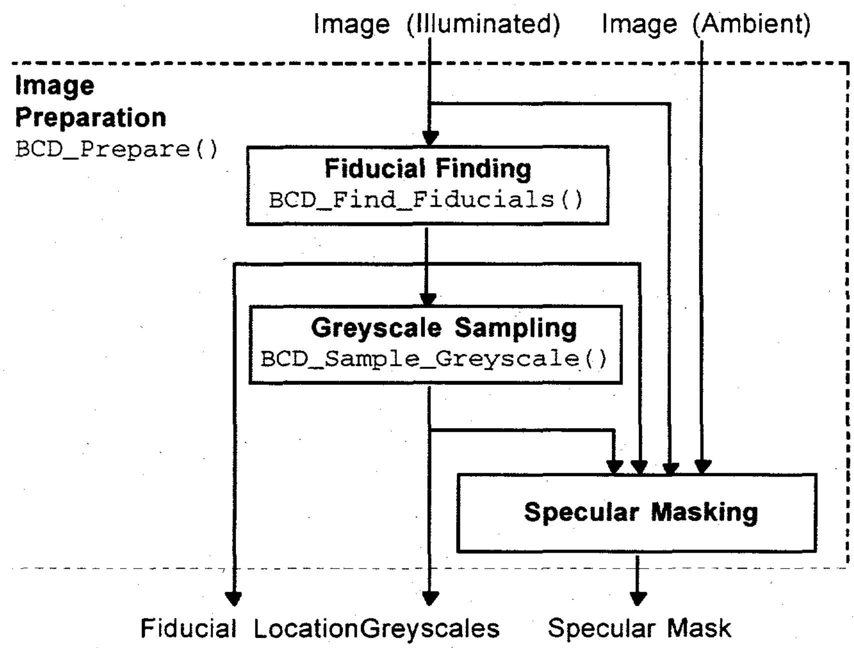


Figure 3: Image preparation

Fiducial finding was implemented in Phase 2 using a correlation-based template-matching approach. Karin Sye of LMMS assisted with the coding of this module. The implementation supports the specification of an ROI (region of interest) in order to limit the search area. This enables improved performance in situations where the location of the marker is expected to lie within a specific area in the image. For example, MISS EVE presently acquires four images of each drum for ABCD (see Figure 4). In each quadrant, the fiducial marker always appears in roughly the same area of the image. Therefore, an ROI can be used on MISS EVE to speed up the search.

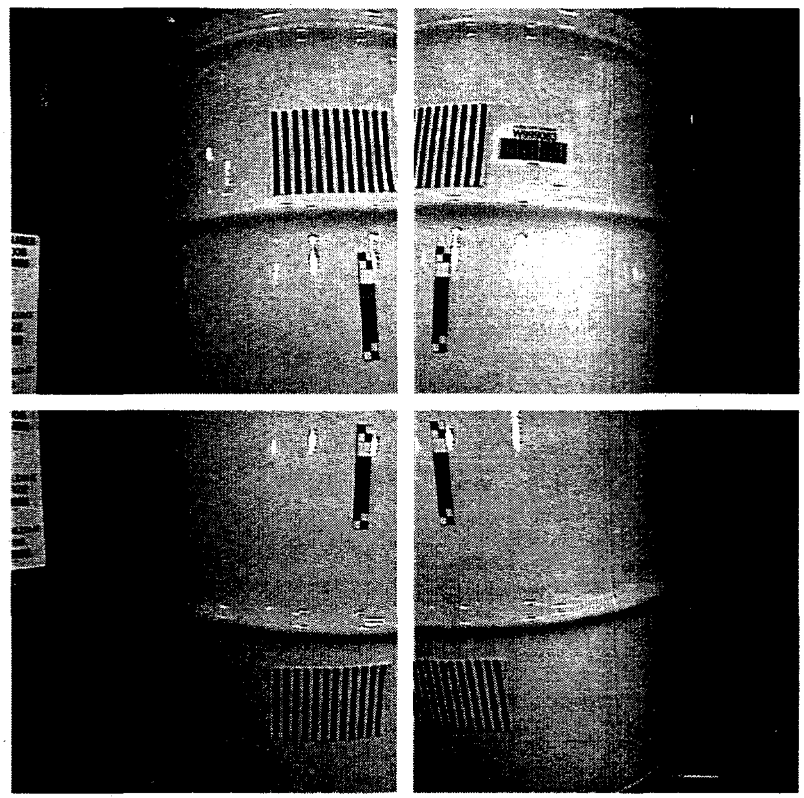


Figure 4: Four images taken of each drum

The ambient-subtraction-based specular masking algorithm demonstrated in Phase 1 was implemented in Phase 2 as illustrated in Figure 5. This algorithm uses two images acquired in rapid succession: an image of the drum illuminated by the IMSS, and an image of the drum as seen with ambient lighting only. This approach assumes: that ambient lighting is constant in the two images; and that the introduction of IMSS lighting causes an increase in pixel intensity that is linear over the entire image except at specular reflections, where pixel intensity increases dramatically.

In this approach, the pixel intensities in the two images are normalized with respect to each other using the greyscales sampled from each image. A specular mask can then be built by identifying all pixels whose intensities appear to be significantly different in the two normalized images. The morphology operations used here consisted of a 3x3 dilation followed by three successive 5x5 erosions.

When ABCD was integrated into MISS EVE, it was discovered that the resolution of on-board camera shutter control was inadequate to produce reliable ambient images. Therefore, a simpler specular masking method was also implemented (see Figure 6). In this approach, all pixels whose intensities lie above a certain fixed threshold are considered to be part of specular reflections and are masked out. In addition, the morphology operations were reduced to a 3x3 dilation followed by a single 5x5 erosion in order to reduce computation.

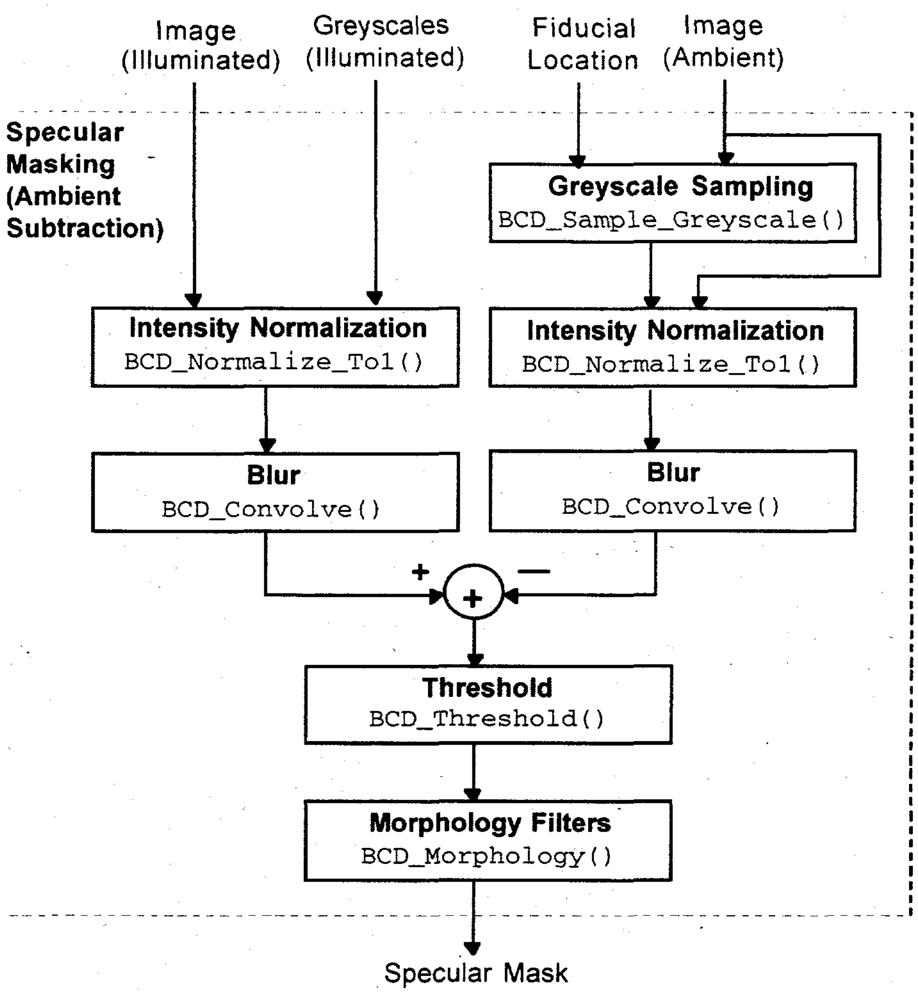


Figure 5: Specular masking using ambient subtraction

The fixed-threshold approach does not require an ambient image, but is only able to cope with a limited set of illumination conditions. Furthermore, it will only mask out the brightest spots in a specular reflection due to the fixed threshold and the reduced number of erosion operators applied. The ambient-subtraction approach is able to compensate for different illuminated objects and for different ambient and vehicle lighting conditions, but requires adequate camera control in order to acquire useful ambient images. The images shown in Figure 7 show specular masks generated from both approaches. In the mask images, black areas represent masked-out areas.

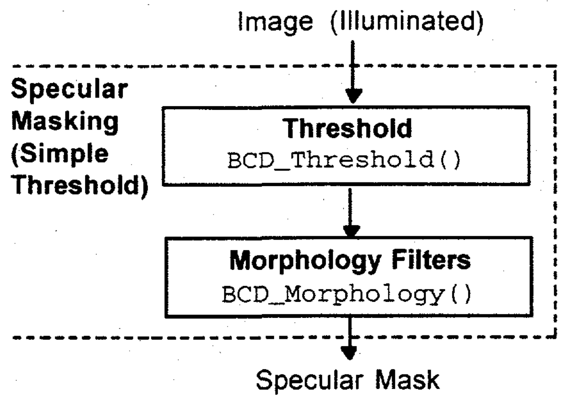


Figure 6: Specular masking using simple thresholding

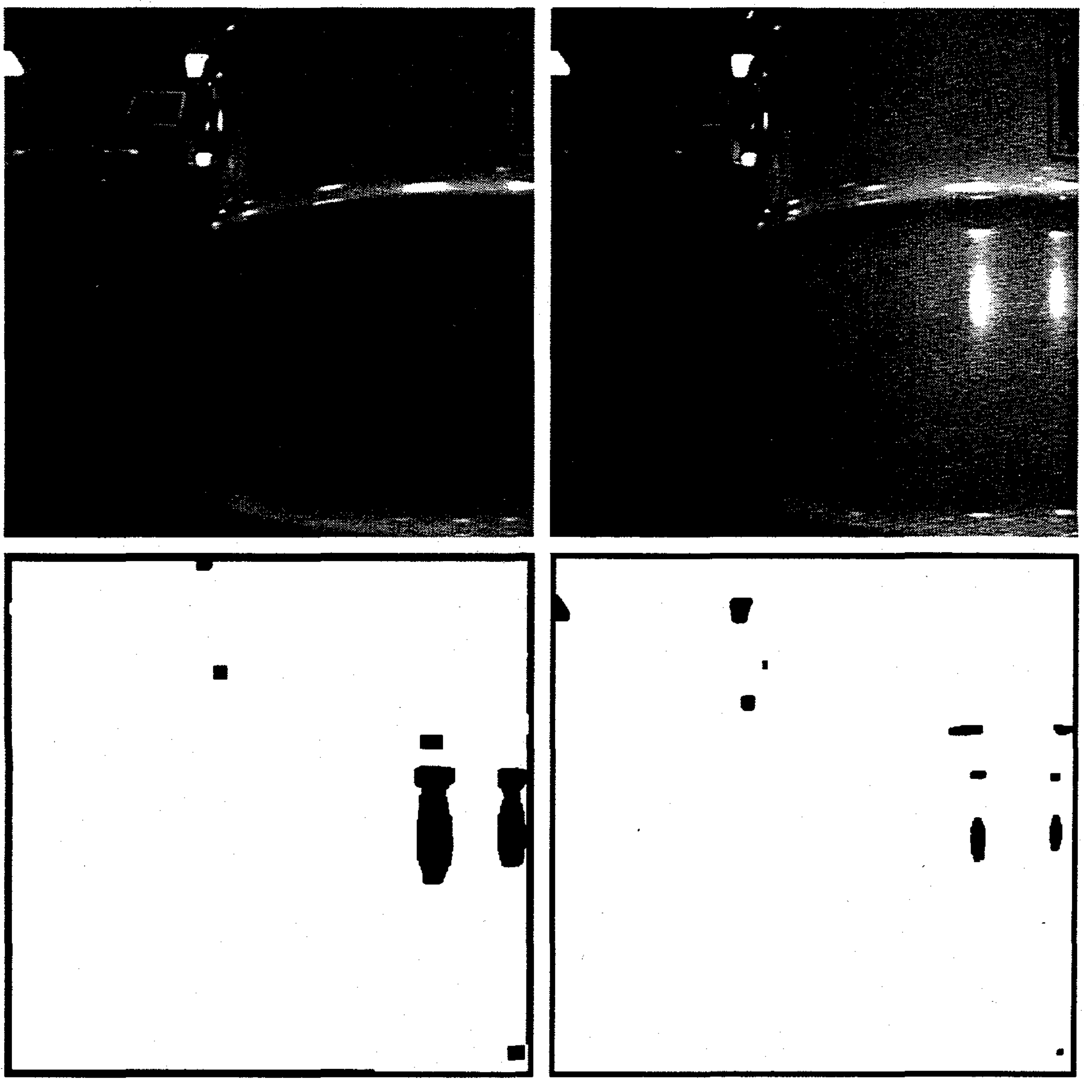


Figure 7: Specular masking results
(clockwise from top-left: ambient image, illuminated image, specular mask using fixed threshold, specular mask using ambient subtraction)

5.4 Intensity Normalization

Intensity normalization compensates for slight variations in illumination over different images taken of the same drum. This enables the quantitative comparison of pixel values from the different images, the basis for image subtraction. In the ABCD system, the inspection image is normalized with respect to the baseline image using greyscales that were sampled from each image during Image Preparation. A first-order polynomial fit is used to remap the pixel values. Figure 9 show some sample images.

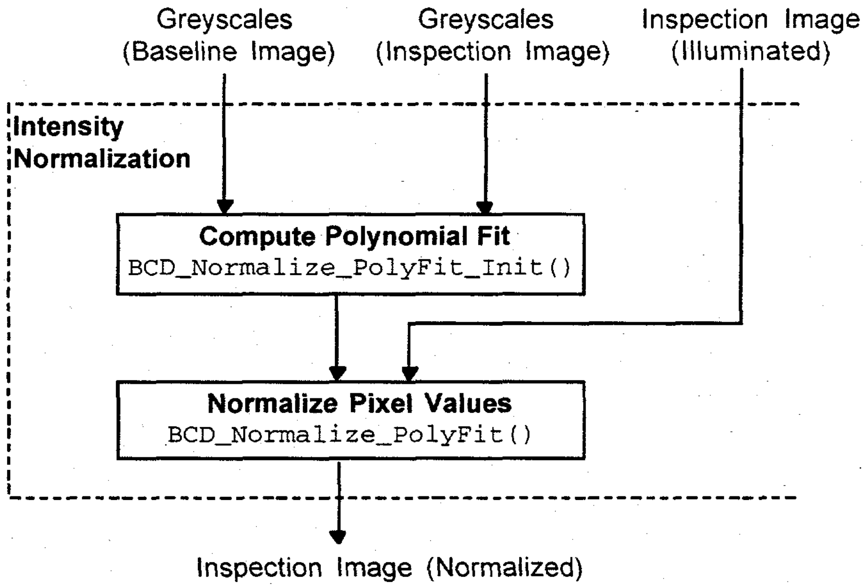


Figure 8: Intensity normalization

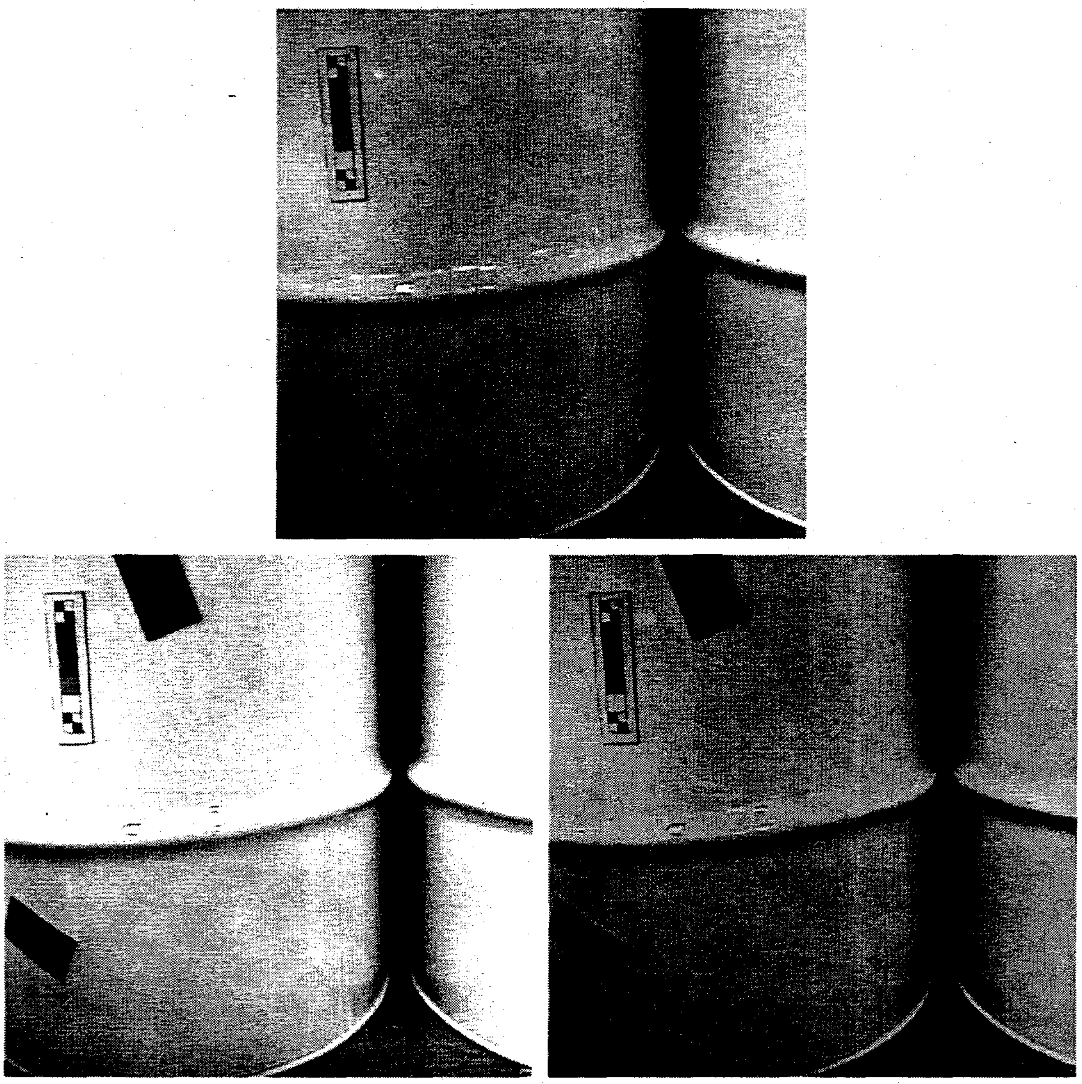


Figure 9: Intensity normalization results
(clockwise from top-left: baseline image, normalized inspection image, inspection image)

5.5 Image Registration

Figure 10 illustrates the implementation of Image Registration. The smoothing filter was implemented as a Laplacian-of-Gaussian filter. As discussed in Phase 1, faint diagonal bands are present in images captured on board the IMSS. This could be caused by electrical noise in the mast of the vehicle. Therefore, a deadband filter was added to remove most of this noise, thereby preventing the tiled registration algorithm from misinterpreting the noise as legitimate texture in the image.

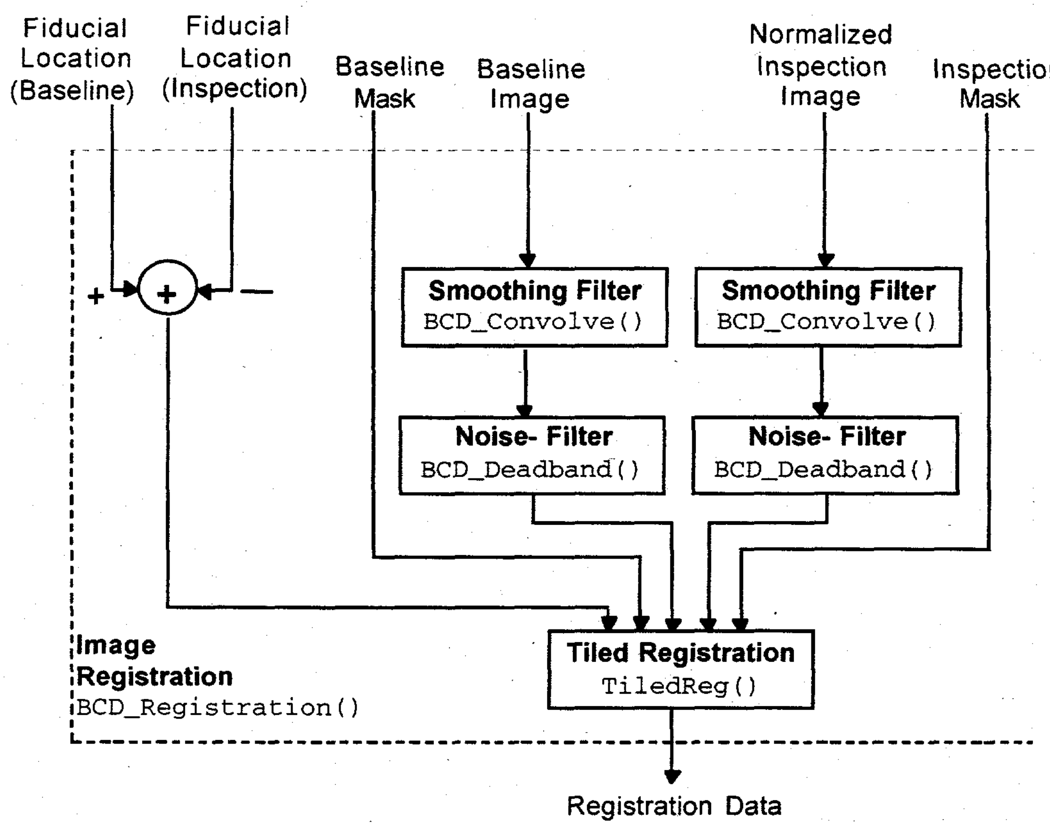


Figure 10: Image registration

The tiled registration algorithm divides the images into small tiles, and attempts to register each tile using subpixel registration based on image texture. As indicated in Figure 10, the tiled registration algorithm is "seeded" with an initial shift estimate derived from the position of the drum label in each image. With this initial estimate, it is able to register the first ("central") tile. It then moves outward, progressively registering individual tiles until all tiles are done. In situations where a tile contains insufficient image texture to produce reliable registration, its registration is inferred based on the results of neighbouring tiles. Masked pixels are not considered.

Due to the limited computing power on board MISS EVE, the tiled registration algorithm was disabled. Instead, a simple "global shift" with subpixel interpolation was applied across the entire image, using the shift estimate derived from the positions of the drum labels. This simplified approach assumes that image registration error is uniform across the entire image. However, this is not true if, for example, camera positioning error has any rotational component.

To illustrate, Figure 11 shows the results of registration and subtraction performed on images acquired at LMA (Denver) during endurance testing. In this case, there was a slight rotational error (approximately 1 degree) in IMSS vehicle/camera positioning. Additional images are provided in Appendix A. In these types of situations, the global shift approach is clearly inadequate.

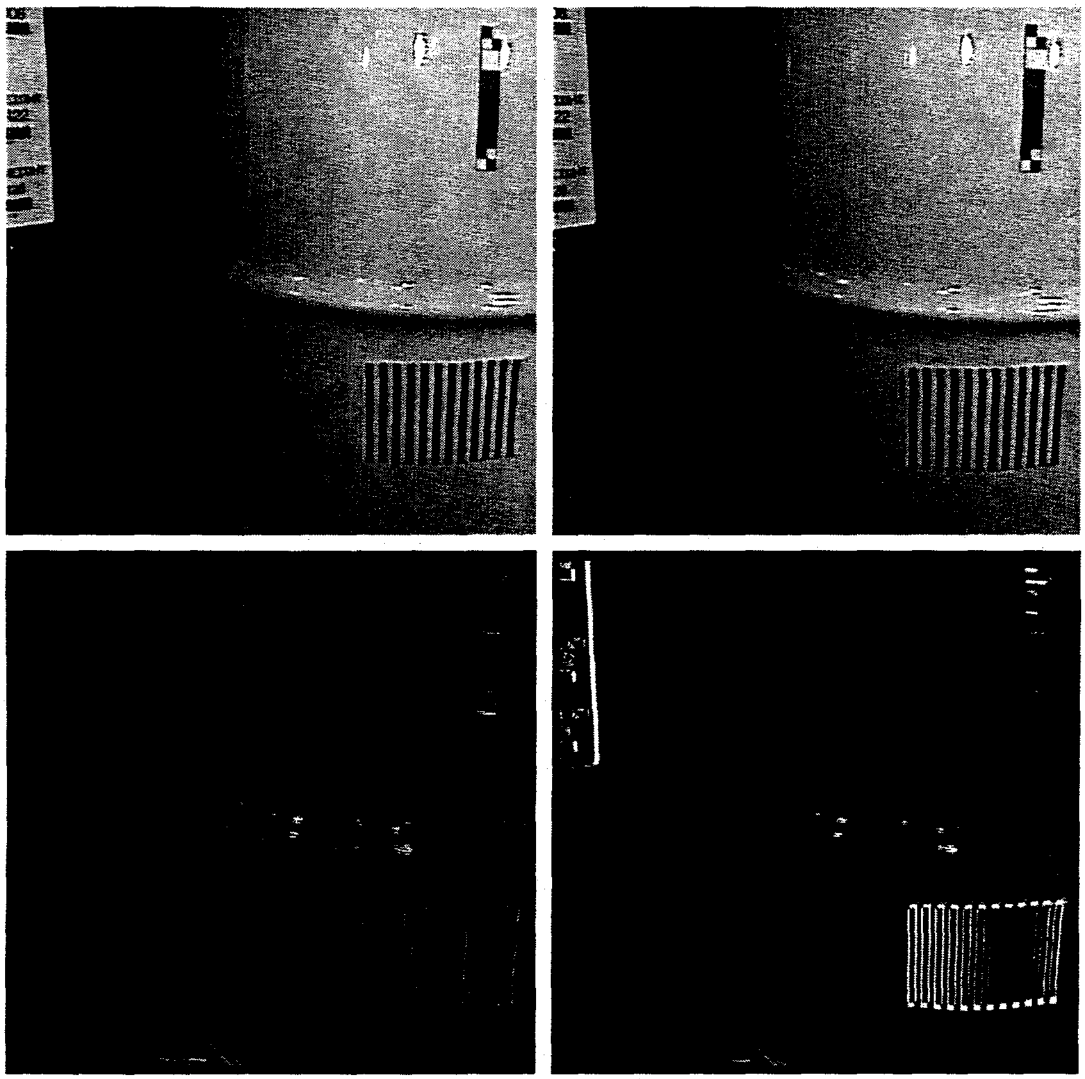


Figure 11: Tiled registration versus "global shift"
(clockwise from top-left: baseline image, inspection image, subtraction image using "global shift", subtraction image using tiled registration)

5.6 Image Subtraction

In tiled image subtraction, the registration results generated by Tiled Registration are used to shift individual tiles (with subpixel interpolation) and perform image subtraction on each tile. Masked pixels are not considered. In the case where the "global shift" approach has been used for image registration, the tiled subtraction algorithm simply considers the entire image to be one large tile. For examples of subtraction images, please refer to Figure 11.

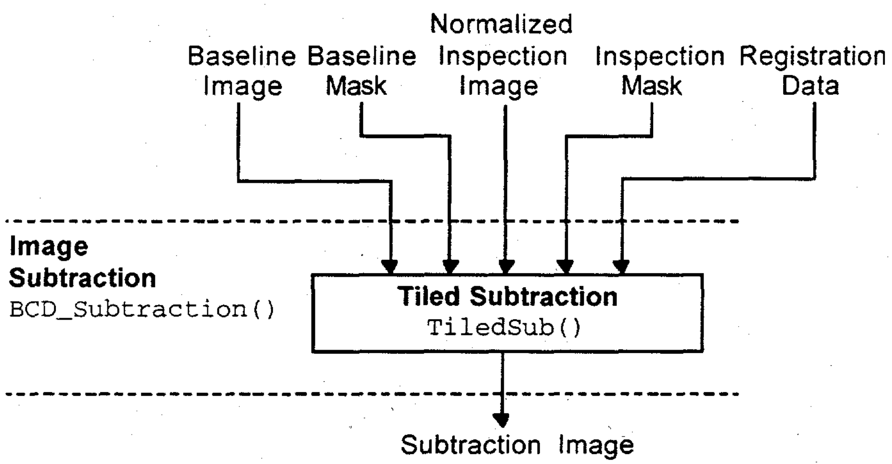


Figure 12: Image subtraction

5.7 Blob Extraction

In blob extraction, the subtraction image is segmented into regions ("blobs") that represent potential defects. First, the absolute value is taken of the subtraction image; then, the result is filtered (3x3 erosion followed by 3x3 dilation); and finally, the image is thresholded and segmented, and statistics about each segmented region are computed. A segmented image is also produced, with each region tagged by a different pixel value. Figure 14 shows some sample results.

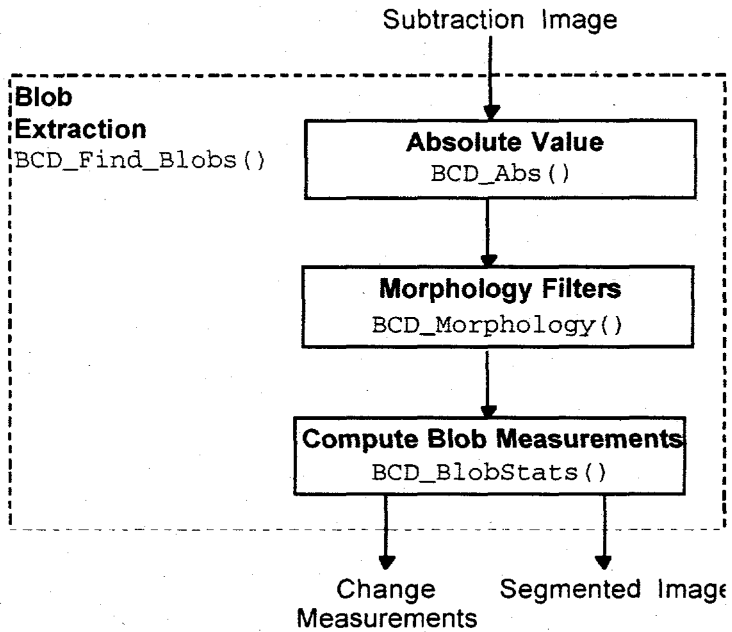


Figure 13: Blob extraction

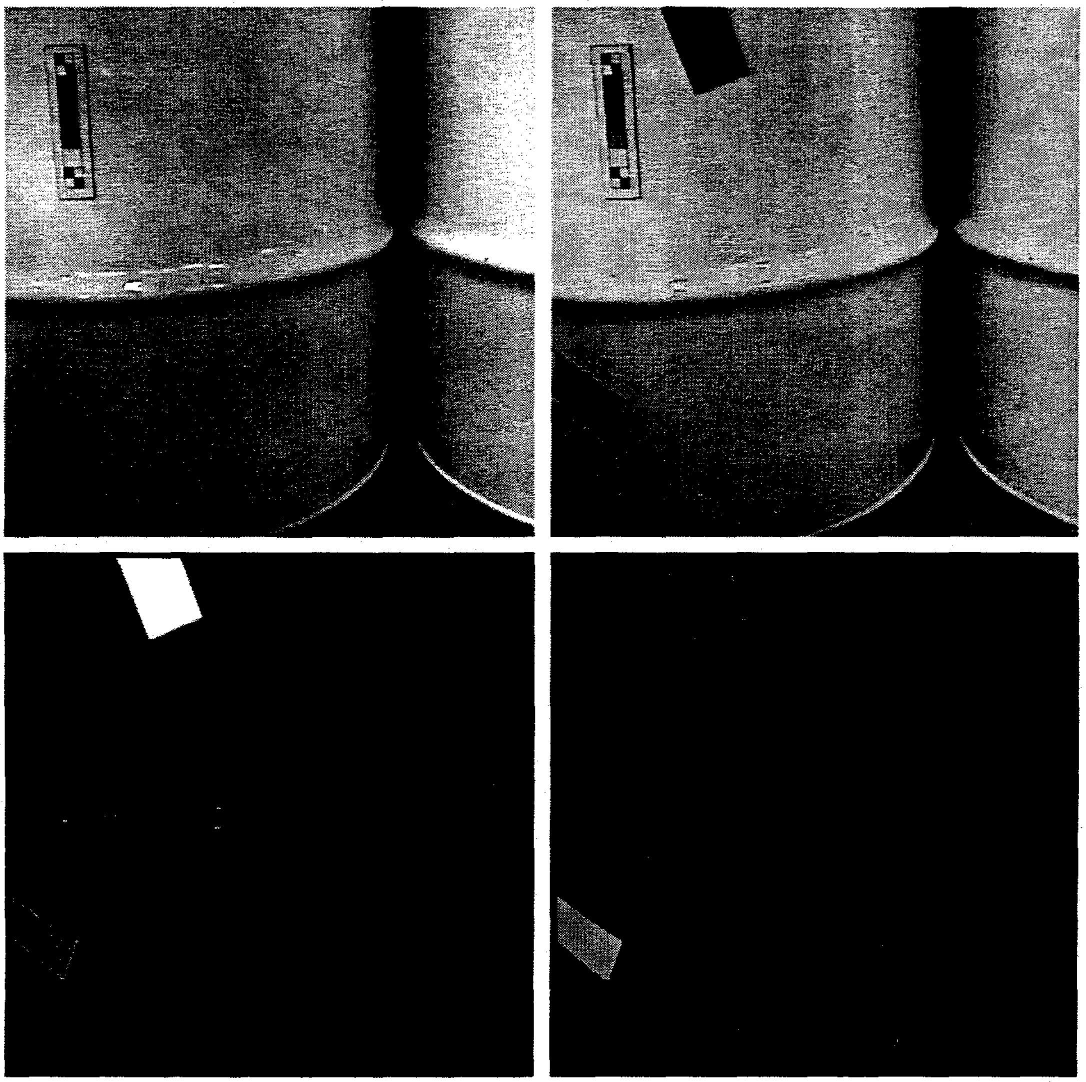


Figure 14: Blob extraction results
(clockwise from top-left: baseline image, normalized inspection image, segmented image, subtraction image)

5.8 Summary of Code Modules

The following is a list of the ABCD source code files (note: only major code modules are indicated here). Phase 2 software development was performed at KSI on an SGI Indigo^2 running IRIX 5.3. Cross-platform portability was tested at KSI using an Intel Pentium computer running SCO UNIX 4.2. At LMA, the ABCD code was also successfully compiled and tested under SunOS and VxWorks (running on MISS EVE's on-board DSPs).

Filename	
Code Module	*Description*
BCD_Errors.c	
BCD_ErrorMsg()	Converts a BCD error status to an error message
BCD_Threshold.c	
BCD_Threshold()	Thresholds an image
BCD_Abs()	Computes the absolute value of an image
BCD_Deadband()	Applies a deadband filter to an image
BCD_Convolve.c	
BCD_Convolve()	Computes the convolution of a kernel with a region of interest (ROI) in an image
BCD_Correlate()	Computes the correlation of a pattern and an ROI
BCD_Morphology()	Applies a morphology filter (erosion/dilation) to an ROI
BCD_Find_Fiducials.c	
BCD_Init_Find_Fiducials()	Initialization for BCD_Find_Fiducials()
BCD_Find_Fiducials()	Locates an ABCD fiducial marker in an ROI
BCD_Normalize.c	
BCD_Normalize_PolyFit_Init()	Initialization for BCD_Normalize_PolyFit()
BCD_Normalize_PolyFit()	Normalizes the pixel values of an image using a first-order polynomial fit
BCD_Normalize_To1()	Normalizes the pixel values of an image to the range [0,1]
BCD_Prepare.c	
BCD_Init_Prepare()	Initialization for BCD_Prepare()
BCD_Prepare()	Prepares an image: locates fiducial marker, samples greyscales, constructs specular mask
BCD_Registration.c	
BCD_Init_Registration()	Initialization for BCD_Registration()
BCD_Registration()	Performs image registration with subpixel interpolation
BCD_TiledRegistration4.c	
TiledReg()	Computes tiled registration of two laplacian-of-gaussian smoothed images
BCD_SubpixelRegistration4.c	

ComputeSubpixelReg()	Computes subpixel registration via sum of absolute difference between two laplacian-of-gaussian smoothed images
BCD_Sample_Greyscale.c	
BCD_Init_Sample_Greyscale()	Initialization for BCD_Sample_Greyscale()
BCD_Sample_Greyscale()	Computes the average pixel intensity around a series of locations (sampling points) in an image
BCD_SubpixelShiftDiff3.c	
SubtractwSubpixelShift()	Computes the difference of two image regions that are shifted by a fractional pixel amount; used by TiledSub()
BCD_Subtraction.c	
BCD_Subtraction()	Performs image subtraction
BCD_TiledSubtraction2.c	
TiledSub()	Computes tiled subtraction of one image from another
BCD_Find_Blobs.c	
BCD_Find_Blobs_Init()	Initialization for BCD_Find_Blobs()
BCD_Find_Blobs()	Thresholds and segments an image
vtest.c	
main()	Stand-alone program for testing BCD modules
fake_vista.h	
—	Functions used by the test driver program (vtest.c); for compatibility with the *Vista* image processing environment developed at the University of British Columbia
BCD_Lib.h	
—	Definitions, macros, prototypes of all BCD functions
Makefile	
—	UNIX makefile

5.9 Timing Results

The timing results shown in Table 1 illustrate the relative computational demands of the various stages in ABCD processing. The software was executed on an SGI Indigo^2 workstation with 32 MB RAM. Here, *Image Set 1* corresponds to the images shown in Figure 14, and *Image Set 2* corresponds to the images shown in Figure 11. Note that the processing times shown here include file I/O for saving intermediate results to disk, and no ROI features were used to reduce computation. On MISS EVE, most of this file I/O is not necessary, and ROIs are used to speed up computation. For comparison, MISS EVE was demonstrated to take approximately 2 minutes 45 seconds to process a 5-level stack of drums at INEL (note that since MISS EVE uses parallel processing, the 2:45 stack processing time is not equivalent to 20 image sets processed in sequence, at 8.25 seconds per image set).

Table 1: ABCD timing results

	Image Set 1		Image Set 2	
Processing Stage	*Full*	*Fast*[†]	*Full*	*Fast*[†]
Preparation	7.68	4.08	7.60	4.21
Normalization	0.38	0.44	0.42	0.40
Registration	4.71	0.66	8.42	0.65
Subtraction	0.96	0.87	1.07	0.89
Blob Extraction	1.98	1.92	2.15	1.95
Total (seconds)	15.71	7.97	19.66	8.10

Notes: [†]specular masking using fixed threshold and fewer morphology operations, and registration using global shift

5.10 Discussion

The Phase 2 implementation of ABCD closely follows the Phase 1 prototype developed on the Macintosh. All functionality demonstrated by the Phase 1 prototype was preserved. However, some important features were disabled upon integration into MISS EVE as a result of operational constraints combined with hardware limitations on board the vehicle.

Specular Masking using ambient subtraction was not used on MISS EVE because insufficient resolution of camera shutter control made it impossible to consistently obtain reliable ambient images. Instead, a simple fixed-threshold approach was used, and the amount of processing was reduced in order to increase throughput. However, this approach is only capable of coping with a limited set of illumination conditions, and can only identify the brightest parts of a specular reflection. Unmasked specular reflections can be mistaken for legitimate image changes, potentially leading to false detection.

Tiled registration was not used on MISS EVE due to the limited computing power of on-board DSPs. Strictly speaking, tiled registration could have been performed, but at the expense of throughput, which could not be compromised due to operational constraints. As a result, a "global shift" approach was used. This simplified approach assumes that image registration error is uniform across the entire image. However, this is only true if camera positioning error does not have any rotational component, and lies solely in the plane perpendicular to the camera axis. The images taken at LMA during endurance testing demonstrate that this is not always true.

Change detection based on image subtraction offers an attractive means to perform difficult and time-intensive inspection of large areas automatically. However, inaccurate registration and specular masking can result in undesirable artifacts appearing in the subtraction image, leading to an increase in false detections and a corresponding increase in dependence on operator supervision. The ABCD project has demonstrated the merit of more sophisticated and robust methods such as specular masking based on ambient-subtraction and tiled registration. These technologies together with the experience gained from the implementation of MISS EVE at INEL should enable us to improve how we manage the volumes of hazardous waste that we produce.

6. ASSESSMENT OF CURRENT STATUS

KSI has completed its Phase 2 work, and is on budget.

7. PLANS

With the submission of this report, KSI completes its involvement in Phase 2.

8. ATTACHMENTS

Appendix A —.Tiled versus Non-tiled Registration

APPENDIX A

Tiled versus Non-tiled Registration

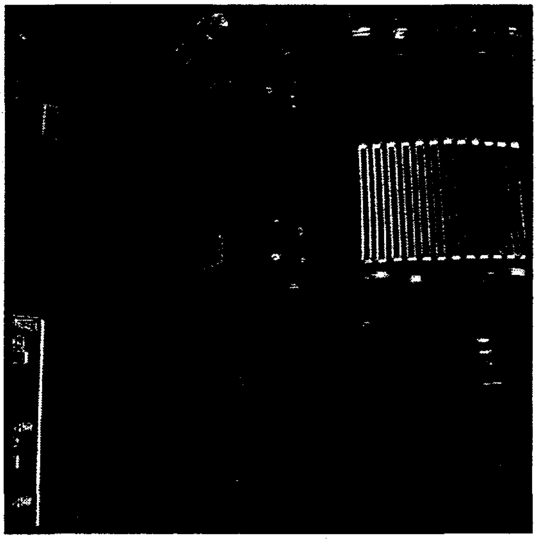
The purpose of this appendix is to provide an idea of the type of results that can be expected from the ABCD system using tiled registration versus the "global shift" registration approach presently implemented on MISS EVE.

The following images were produced by the ABCD system using drum images taken at LMA (Denver) during endurance testing (18 March, 1997). In these images, there was a slight rotational error (approximately 0.5 to 1 degree) in IMSS vehicle/camera positioning. Please note that these sample results were produced with minimal performance tuning. Processing was performed at KSI on an SGI Indigo^2 workstation.

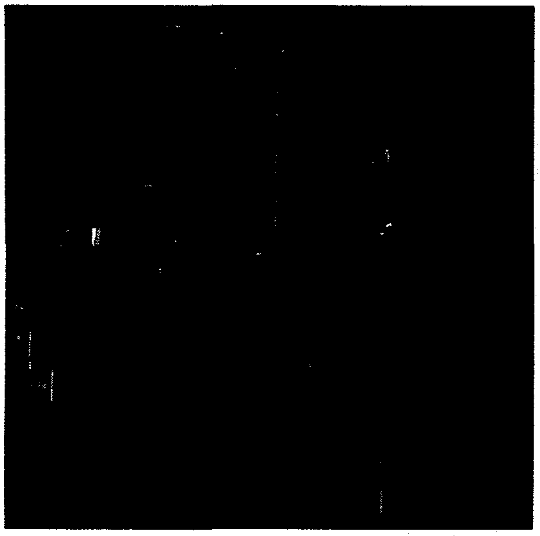
In the following images, the subtraction image resulting from tiled registration is shown on the left-hand side and the corresponding image obtained using the global shift approach is shown on the right.

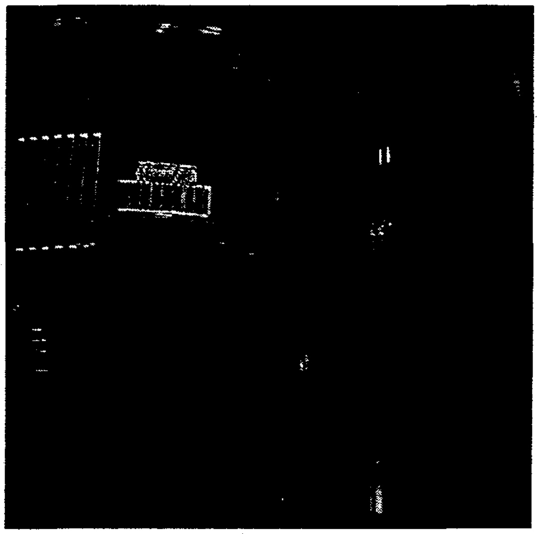
"Moderate" Rotational Error

Top-Left:

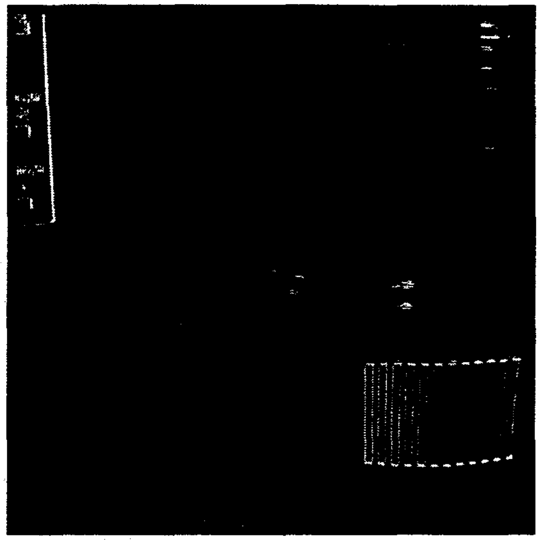


Top-Right:





Bottom-Left:



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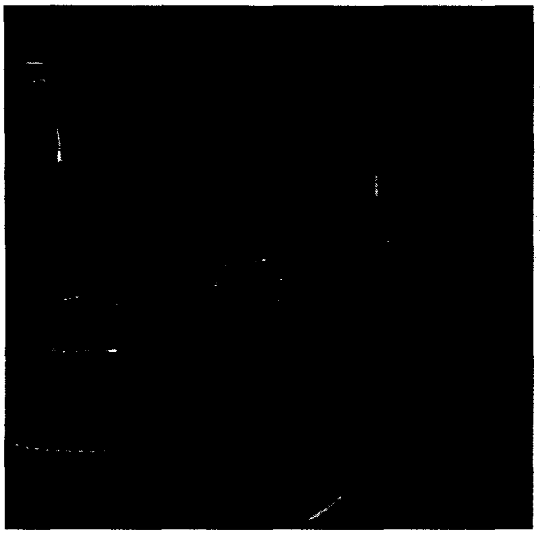
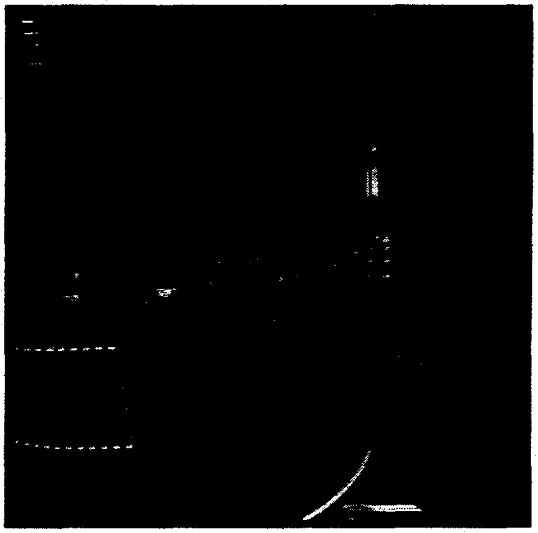
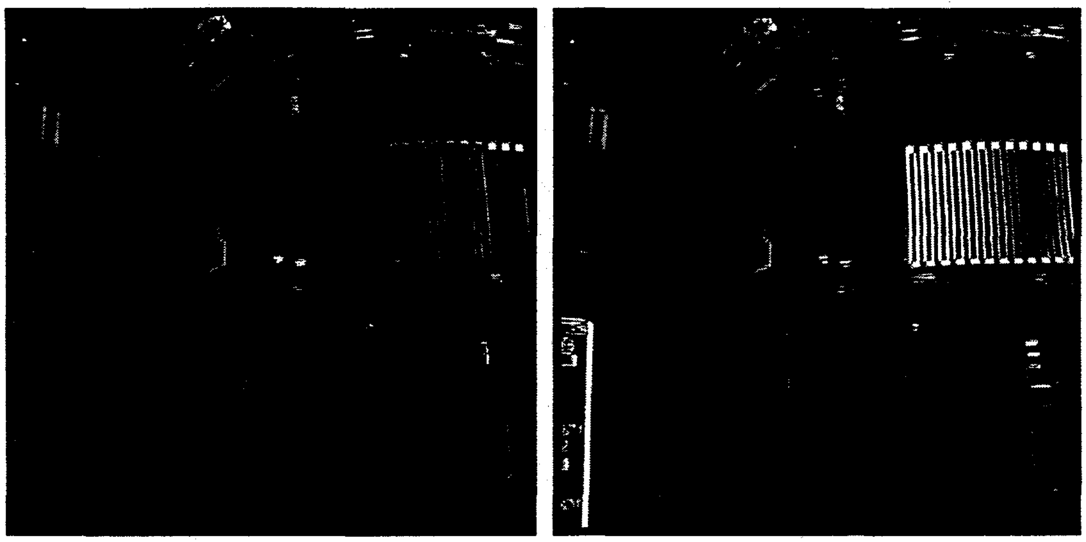


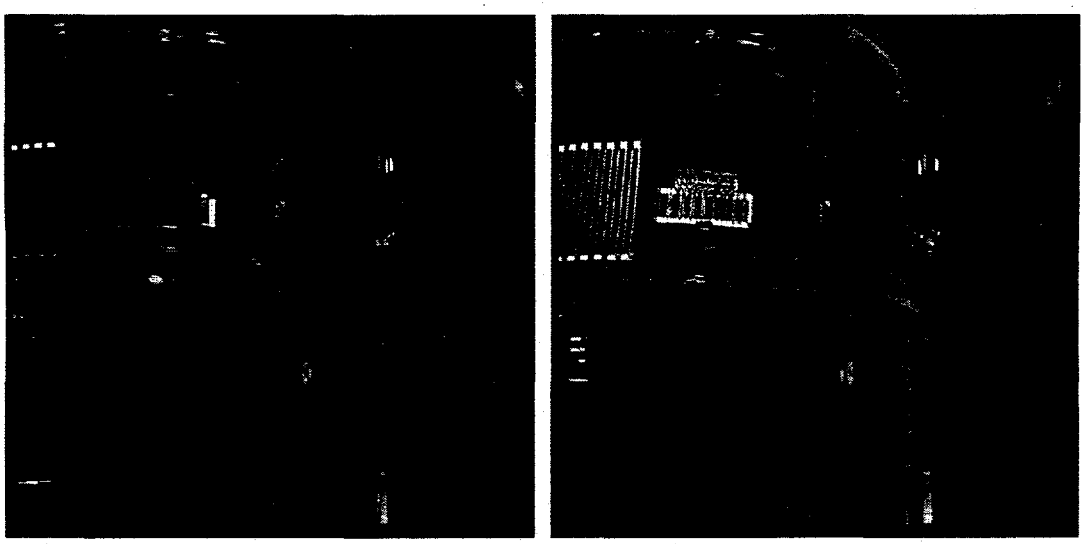


“Large” Rotational Error

Top-Left:



Top-Right:



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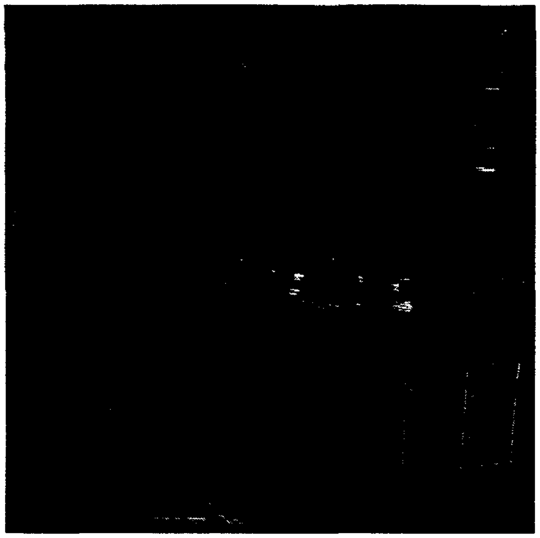

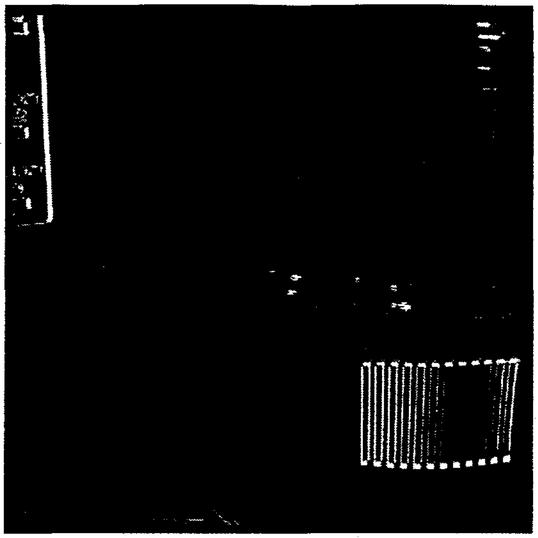

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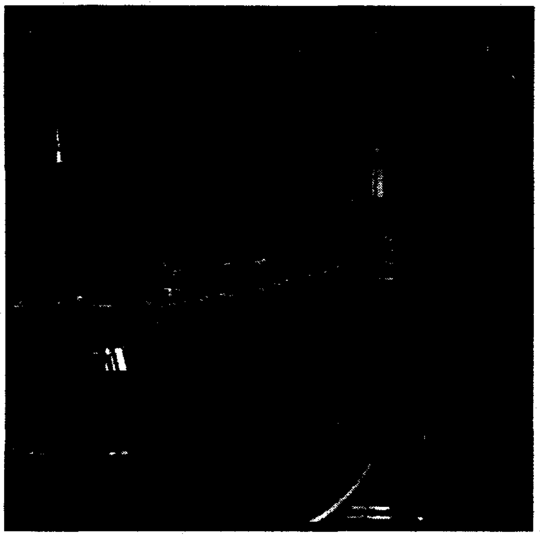

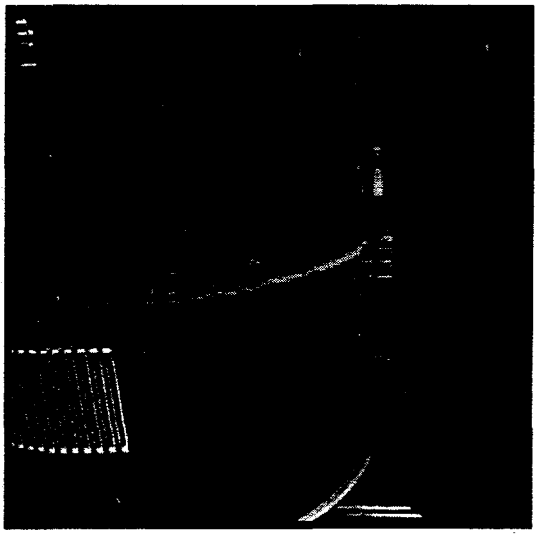

Appendix B

Intelligent Mobile Sensor System
Mobility Base

Intelligent Mobile Sensor System

for

Drum Inspection and Monitoring

Contract Number DE-AC21-92MC29112

Topical Report
for period
October 1st, 1995 - April 30th, 1997

For: U.S. Department of Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By: Lockheed Martin Astronautics
P.O. Box 179
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Original report April 30, 1997

Disclaimer

This work was performed for the Morgantown Energy Technology Center and sponsored by the US Department of Energy, Office of Technology Development.

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Abstract

The objective of the Intelligent Mobile Sensor System (IMSS) project is to develop an operational system for monitoring and inspection activities for waste storage facility operations at several DOE sites. Specifically, the product of this effort is a robotic device with enhanced intelligence and maneuverability capable of conducting routine inspection of stored waste drums. The device is capable of operating in the narrow free aisle space between rows of stacked drums. The system has an integrated sensor suite for problem-drum detection, and creates and maintatins a site database both for inspection planning and for data correlation, updating, and report generation. The system is capable of departing on an assigned mission, collecting required data, recording which portions of its mission had to be aborted or modified due to environmental constraints, and reporting back when the mission is complete. Successful identification of more than 96% of drum defects has been demonstrated in a high fidelity waste storage facility mockup. Identified anomalies included rust spots, rust streaks, areas of corrosion, dents, and tilted drums. All drums were positively identified and correlated with the site database.

This development effort is separated into three phases of which phase 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 provides an integrated design that considers 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

This project is grateful for the sponsorship of the Department of Energy and Morgantown Energy Technology Center and for the coordination and direction supplied by Cliff Carpenter and Vijay Kothari of those groups. Also we acknowledge and are grateful for field and regulatory evaluation supplied by the Mixed Waste Focus Area, specifically Jay Roach and Brad Gardener. We appreciate the guidance and operational requirements contributed by key personnel at the various waste storage and remediation facilities, most notably: Brack Hazen at Fernald, Davis Christensen at Los Alamos National Laboratory, Kim Allison and Dean Lobdell at Rocky Flats Environmental Technology Center, Wyn Schwendiman an Derek Wadsworth at Idaho National Engineering Laboratory, and Loretta Huber at Lawrence Livermore National Laboratory. We also appreciate the peer review and contacts supplied by Clyde Ward and Dave Wagner of Westinghouse Savannah River, the time spent by the Waste Operations Groups at Oak Ridge National Laboratory, and aid with applications context provided by Hanford Engineering Laboratory.

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. 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. The description of basic requirements, background material, and many fundamental design features are retained from the Phase 1 documentation, and have been updated to reflect the 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.

2. PURPOSE

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

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

Representative EPA and DOE approved inspection procedures from Hanford and Rocky Flats are presented and discussed in the next section. From these requirements, and from discussions with waste operations personnel at four DOE sites (Oak Ridge National Laboratory, Hanford Engineering Laboratory, Idaho National Engineering Laboratory, and Rocky Flats Plant), the functional requirements shown in Table 3-1 were developed during Phase 1. Other derived requirements are shown in Table 3-2.

Table 3-1. Functional Requirements.

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

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

Several broad operational goals were used to focus the development of this system:

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

Table 3-2. Derived Requirements.

KEY DRIVER	DERIVED REQUIREMENT
Operate in Waste Storage Area	- 20" width for mobility base - sensors operate in dim light - sensor placement device for reaching stacked barrels 20' high or in combination with directional probe or sensor. - proximity sensor for obstacle detection and avoidance
Operate in Contaminated and Hazardous Areas	- design for comtamination control
Safe operation in environment	- fail operational to ensure return to base and no collisions or runaways - non-sparking to avoid volatile combustion - bumper sensor for immediate stop on contact
Perform Mission Without Human Intervention	- Intelligent vehicle executive - map based planner - realtime sensor based control - sensor based replanning
Detect Anomalous Characteristics	- provide background measurement capabilities for volatiles and radiation - detect rust patches, dents, scratches
Log Locations and Characteristics of Anomolous Measurements	- provide data archiving on board vehicle - transmit to console at mission end - provide navigational measurements to locate of events - archive visual information for anomolous events - provide bar code and label reading system
Characterize Nature of Contaminants for related investigations	- modular sensor suite for multiple instruments - be able to install instruments for detailed investigation of leaks (eg. spectrometers) - sample collection system
Provide Realtime Control and Feedback to Operators if Necessary	- allow direct operator control of all automous operations as necessary - communication link - supply direct teleoperated control - provide display of vehicle location, site map, measurement data and vehicle status
Generate Inspection and Monitoring Reports	- be able to operate on database to select and correlate desired information - automatically print out reports after inspection
Report Mission Status	- executive planner must record status of its tasks - auto print map and path
Accomodate Future Unknown Tasks	- modular interfaces for additional equipment (data, electrical, mechanical) - extra space on top of vehicle

3. BACKGROUND

3.1 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 **Error! Reference source not found.** were developed during Phase 1. A further discussion of these requirements and procedures occurs below. It is noted that few specifics are provided in the documentation and consistency between sites is not maintained.

Most storage facilities have drums stored four to a pallet and have pallets stored in single rows. Stacking heights varied from two to five drums with an average of three. Aisle widths varied from 26" to 36". Aisle lengths varied from 20 feet to hundreds of feet. In general, space was left between the last pallet in a row and the adjacent wall. Positive inspection of each drum is required. Operator response to flagged drums is required within 24 hours. All drums must be inspected every six days.

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

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

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

From these rules and guidelines the following drum inspection requirements were incorporated:

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

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

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

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

Table 4-1. Waste Storage Facility Inspection Procedures Extract (Hanford) for RCRA Hazardous Waste Container Storage Units.

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

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

3.2 Comparison of Stored Waste Monitoring Techniques

3.2.1 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.

3.2.2 Advantages of Proposed Solution

3.2.2.1 Public and Occupational Health Risks

A major advantage is the reduced human exposure afforded by this system. Inspectors no longer need to enter the building to monitor the stored waste. The extended exposures during normal inspection add up quickly given the required frequency and total number of stored waste containers. Thus, using this autonomous system will eliminate the occupational health risks associated with this activity. This is even more important in the event of a discovery of a leak, or of collapsing drums which have inestimable costs in possible long term injuries. In fact, in the event of a leak, an autonomous system, equipped with a manipulator with advanced impedance control and contact stability algorithms, can use a siphon tool and bung puller to remove the material before removing the drum without risking breaking open full containers during transit.

3.2.2.2 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.

3.2.2.3 Operations

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

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

3.2.2.4 Cost

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

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

- One full time inspection team (two inspectors) costs $150k / year including costs for wages, overhead (suits, sensors, *etc.*), support (exit exam and decontamination, *etc.*), and training.
- Use of time during an 8 hour shift includes 4 hours for inspection, 1 hour for preparation and transit, and 3 hours per day for reporting.
- Inspectors require 16 hours training per month (on average) or 4 hours per week.

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

- Cost of mobile sensor system after initial prototype is $200k / vehicle.
- Vehicle operates 8 hours on, 4 hours recharge per shift, 2 shifts per day.
- Vehicles do <u>not</u> operate on weekends.
- Required support is 30 minutes per trip for task loading and report generation by a human operator; 8 hours per week maintenance (nonproductive time plus labor charge), installation support of $10k per room (beacons and map generation).

Given these assumptions, calculated costs per year for the two different methods are as follows: manned - $150k / year and automated - $210k / year. The calculated productivity for each system in terms of hours of inspection time are: manned 768 hours / year (52 weeks - 2 weeks vacation - 2 weeks holidays = 48 weeks per year. Weekly productivity is 4 hours / day * 5 days / week - 4 hours / week training = 16 hours / week. Total productivity is 48 * 16 = 768) and automated 3744 hours per year (52 weeks per year; weekly 16 hours / day * 5 days - 8 hours maintenance = 72 hours / week. Total productivity is 52 * 74 = 3744). Given these costs and productivity, an overall comparison is shown below:

manned - $195 / hour
automated - $56 / hour

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

3.2.2.5 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.

3.2.2.6 Waste Minimization

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

3.2.2.7 Institutional and Regulatory Goals

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

4. 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.

4.1 Design Process

No modifications are necessary to this section.

4.2 System Overview

No modifications are necessary to this section.

4.3 Subsystem Designs

4.3.1 Mechanical Subsystems

4.3.1.1 Vehicle Structure

While the structure of the vehicle base has remained the same from the Phase 2 vehicle, a fourth level mast extension has been 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.

4.3.1.2 Motion Platform

No modifications are necessary to this section.

4.3.1.3 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 reduces the overall mast weight, and expecially the moment applied to the base. This change requires 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 positioning of 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.

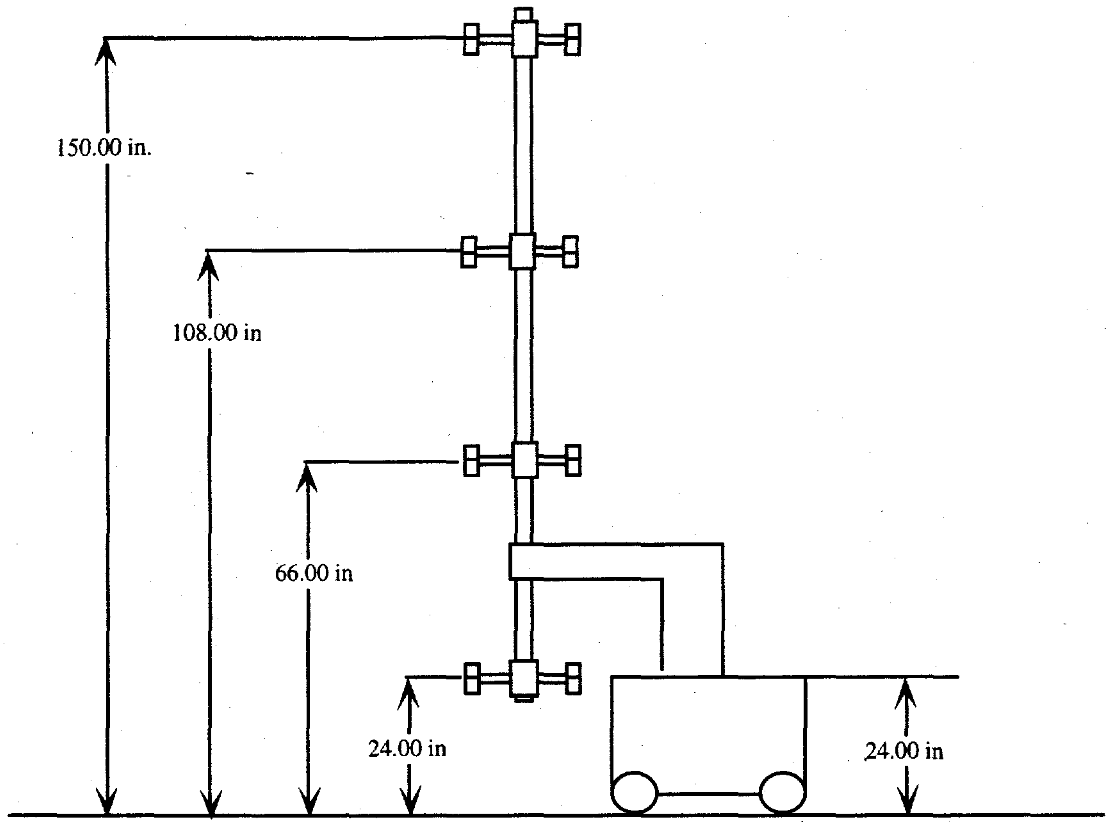

Figure 5-1. Diagrammatic Side View of Phase 3 Vehicle.

4.3.2 Electrical Subsystems

4.3.2.1 Vehicle Electronics

The fundamental configuration of the vehicle electronics is unchanged from the Phase 2 vehicle. The principal phase 3 modifications are 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, with 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 the 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.

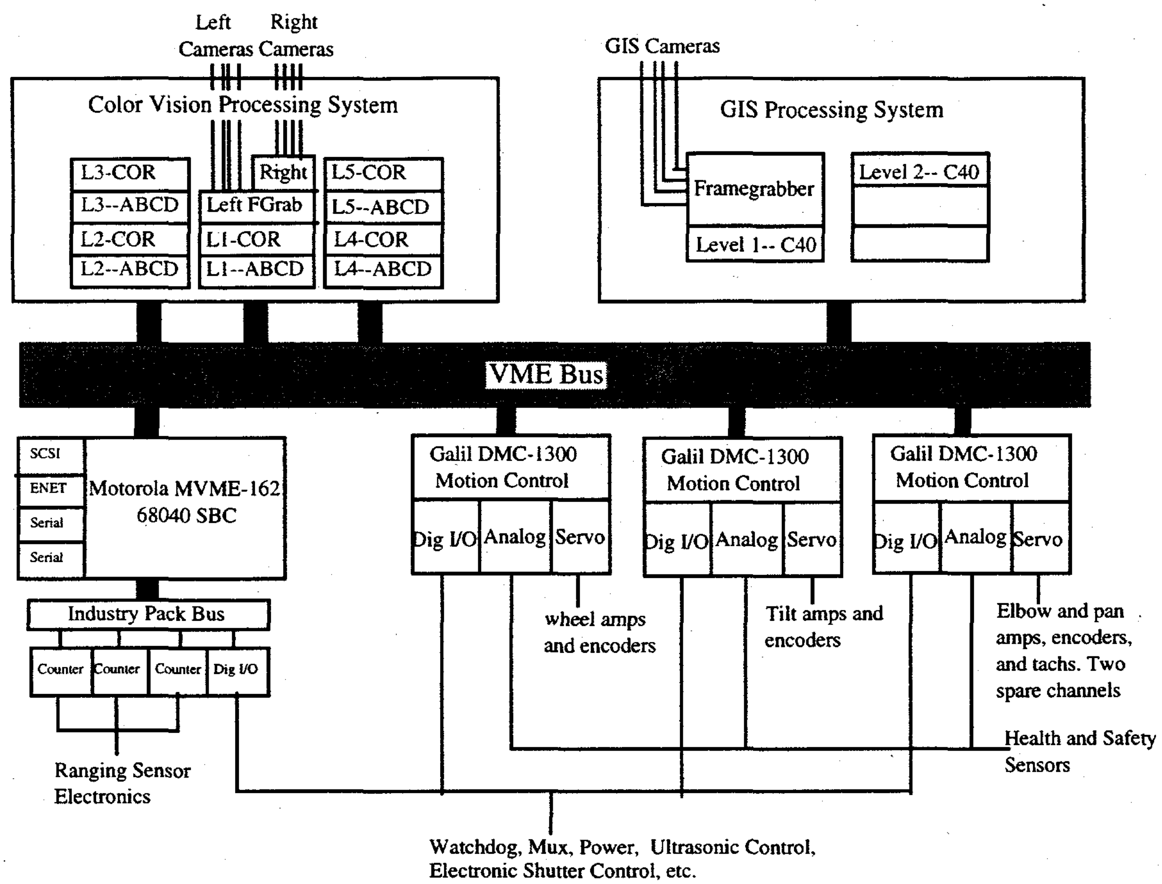

Figure 5-2. Control Electronics Detail.

4.3.2.2 Ultrasonic Sensing

4.3.2.3 Communications

The on-board vehicle communications are unchanged from the Phase 2 vehicle; however, several additions have been made to improve vehicle to base station communications. The first is 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 is implement 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.

4.3.2.4 Power

The primary power subsystem, consisting of 40 NiCD battery cells is 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.

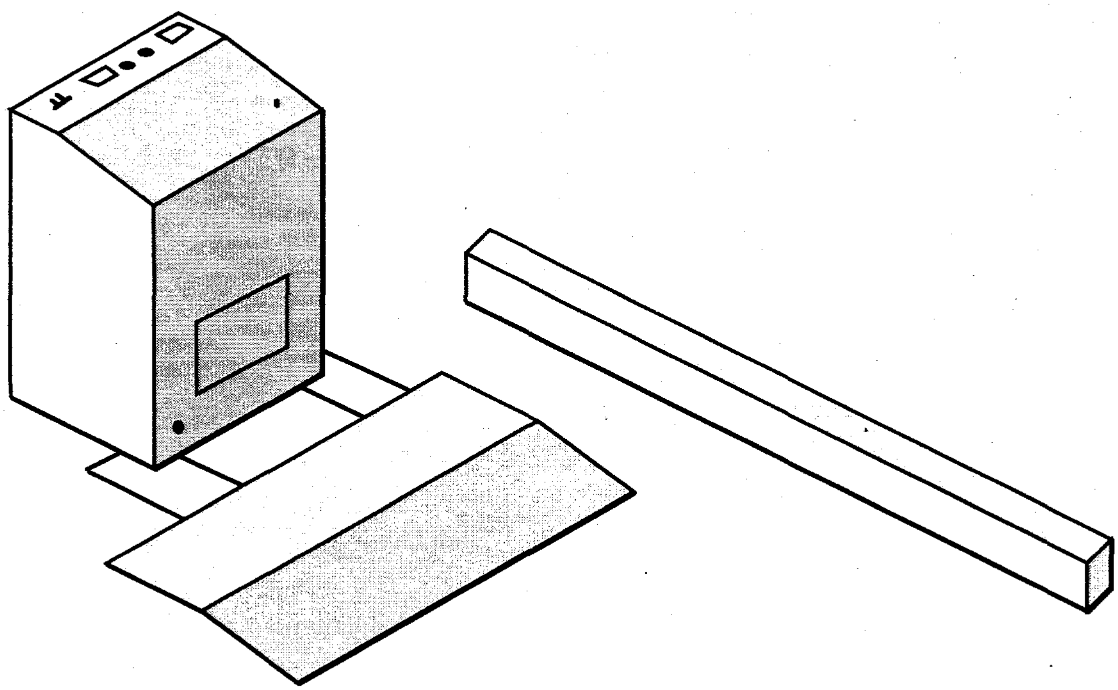

Figure 5-3. Vehicle Docking Station.

4.3.3 Safety System

All of the safety system components described in the Phase 2 report are still in place. In addition, safety interlocks have been 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 is 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.

4.3.4 Control

No modifications are necessary to this section.

4.3.5 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.

4.3.5.1 Dead Reckoning

The information from Phase 2 remains accurate. The number of dead reckoning moves has been 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.

4.3.5.2 Navigating Aisles

The information from the Phase 2 report remains accurate. The process of locating a drum within an aisle has been made more robust. The ultrasonics-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 has been 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 is 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.

4.3.5.3 Finding Aisles

The information from the Phase 2 report remains accurate.

4.3.5.4 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 will abort the failed navigation command, move the vehicle back to the last previously known position, retry 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 is 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 inadvertant vehicle motion. This coupled with the other ultrasonic and skin-based obstacle detection components provide an integrated solution to protecting the vehicle.

4.3.5.5 Docking / Undocking

A new aspect of the navigation subsystem for the Phase 3 vehicle is 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 has been 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.

4.3.6 Mission Sensing Subsystems

4.3.6.1 Geometric Inspection System

No modifications are necessary to this section.

4.3.6.2 Color Vision System

The fundamental concept of the color vision 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 to 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 aquired 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.

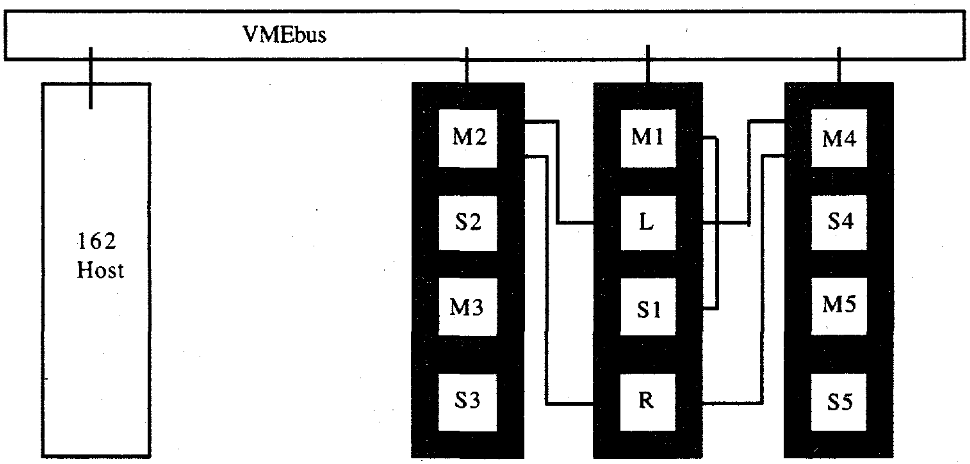

Figure 5-4. Color vision system processor architecture.

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. The, 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 or 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 now 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 checkboard fiducial markers provides a means to normalize the intensity level between the baseline and inspection images.

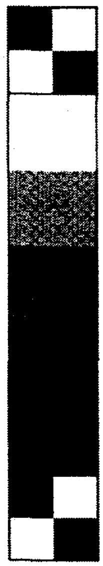

Figure 5-6. Fiducial label.

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.

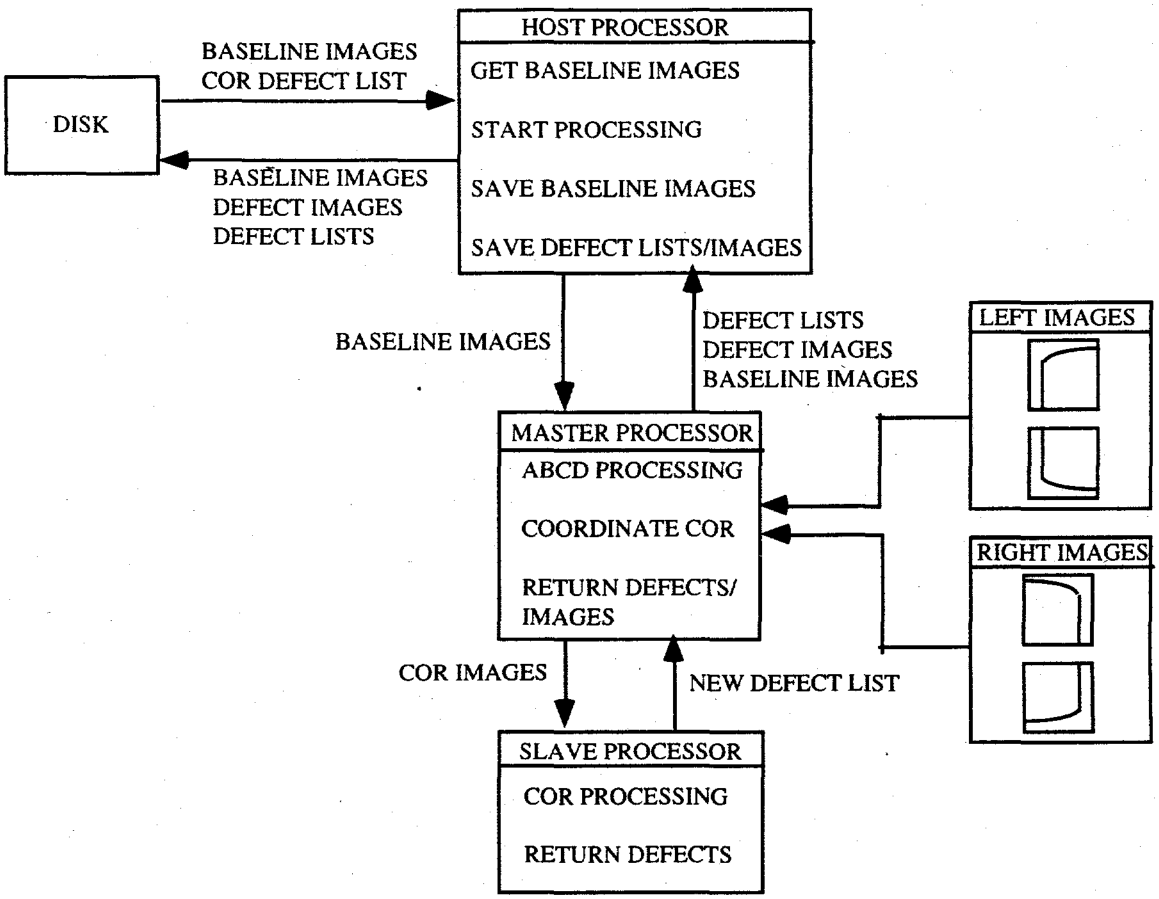

Figure 5-7. Color Vision System Inspection Diagram for One Level.

4.3.6.3 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.

4.3.7 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.

4.3.7.1 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.

4.3.7.2 Facility Model Editor

The facility model editor was complete 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.

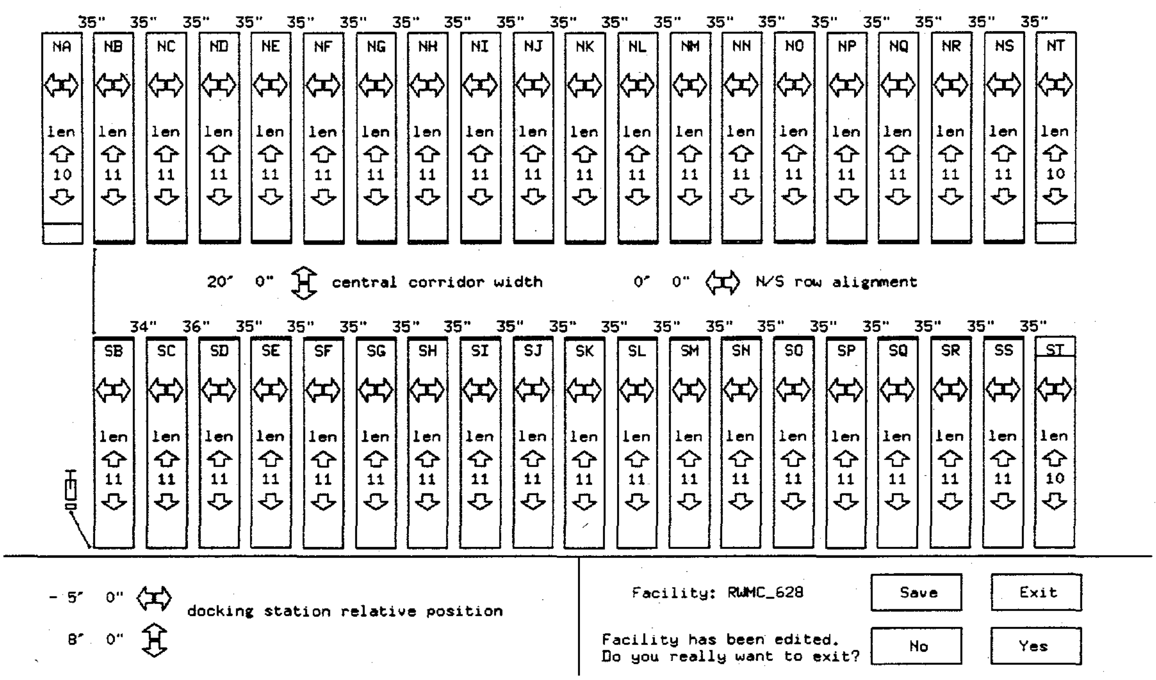

Figure 5-8. Sample Facility Model.

4.3.7.3 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.

4.3.7.4 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. Additonally, 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).

4.3.8 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).

4.4 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 section 5.4 of the Phase 2 report. 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.

4.4.1 Fernald Site (TS-4 Structure)

4.4.1.1 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.

Figure 5-9. FEMP Site configuration.

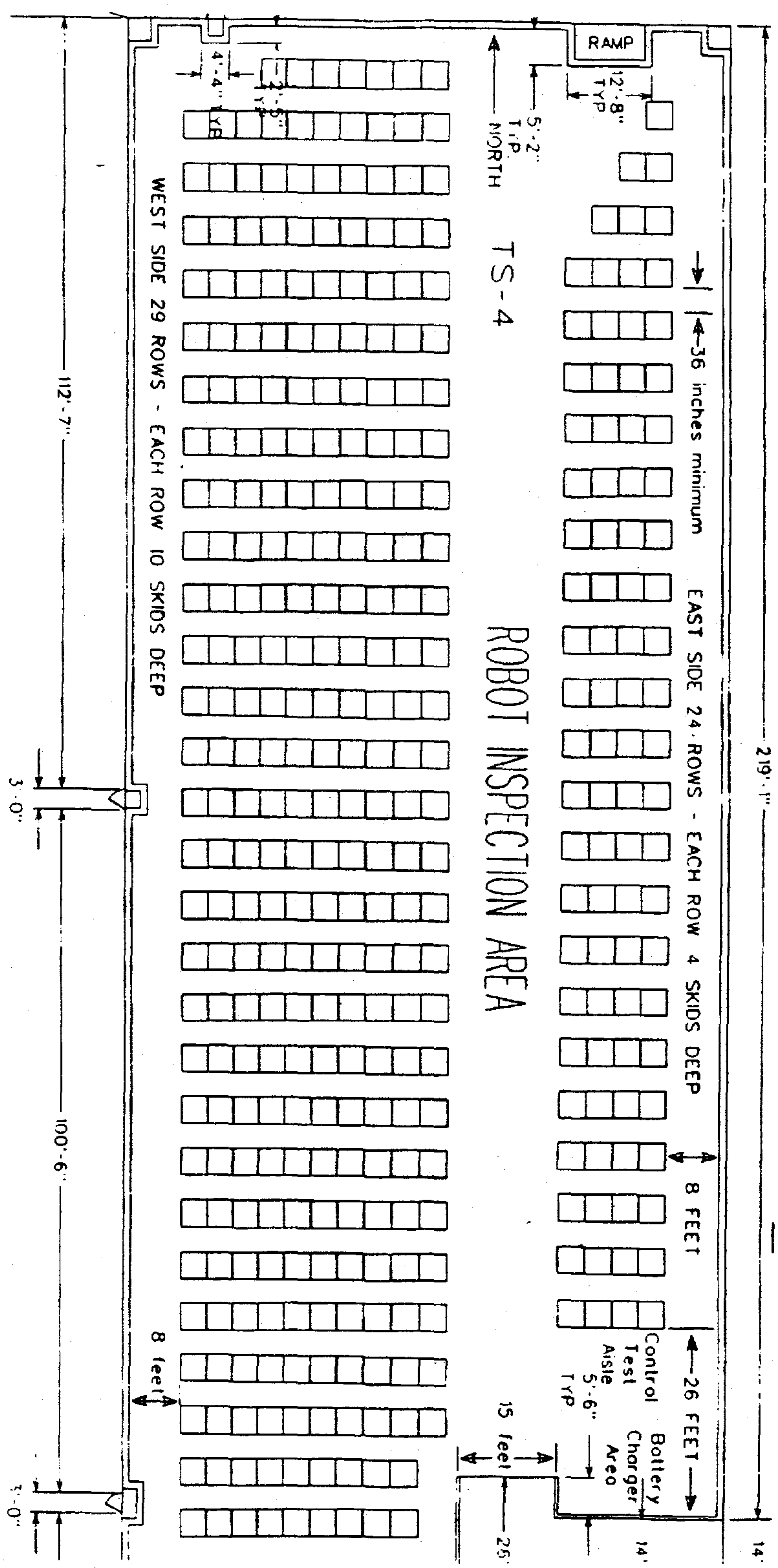

Figure 5-10. TS-4 configuration (North Half).

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 between the workstations and the vehicle in the TS-4 facility.

4.4.1.2 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

4.4.1.3 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.

4.4.2 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.

4.4.3 INEL Radioactive Waste Management Complex (RWMC) Site

4.4.3.1 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.

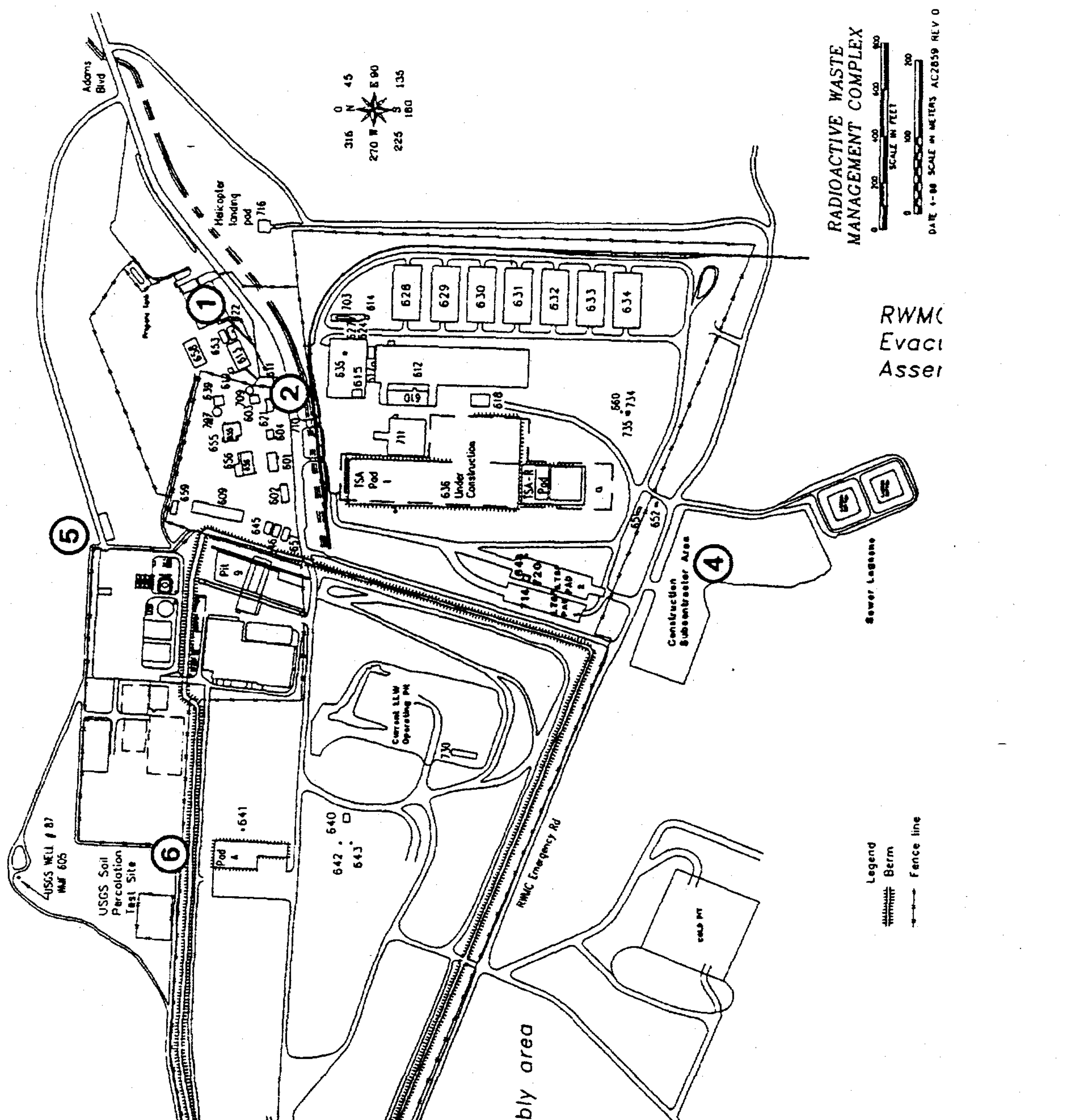

Figure 5-11. The RWMC site.

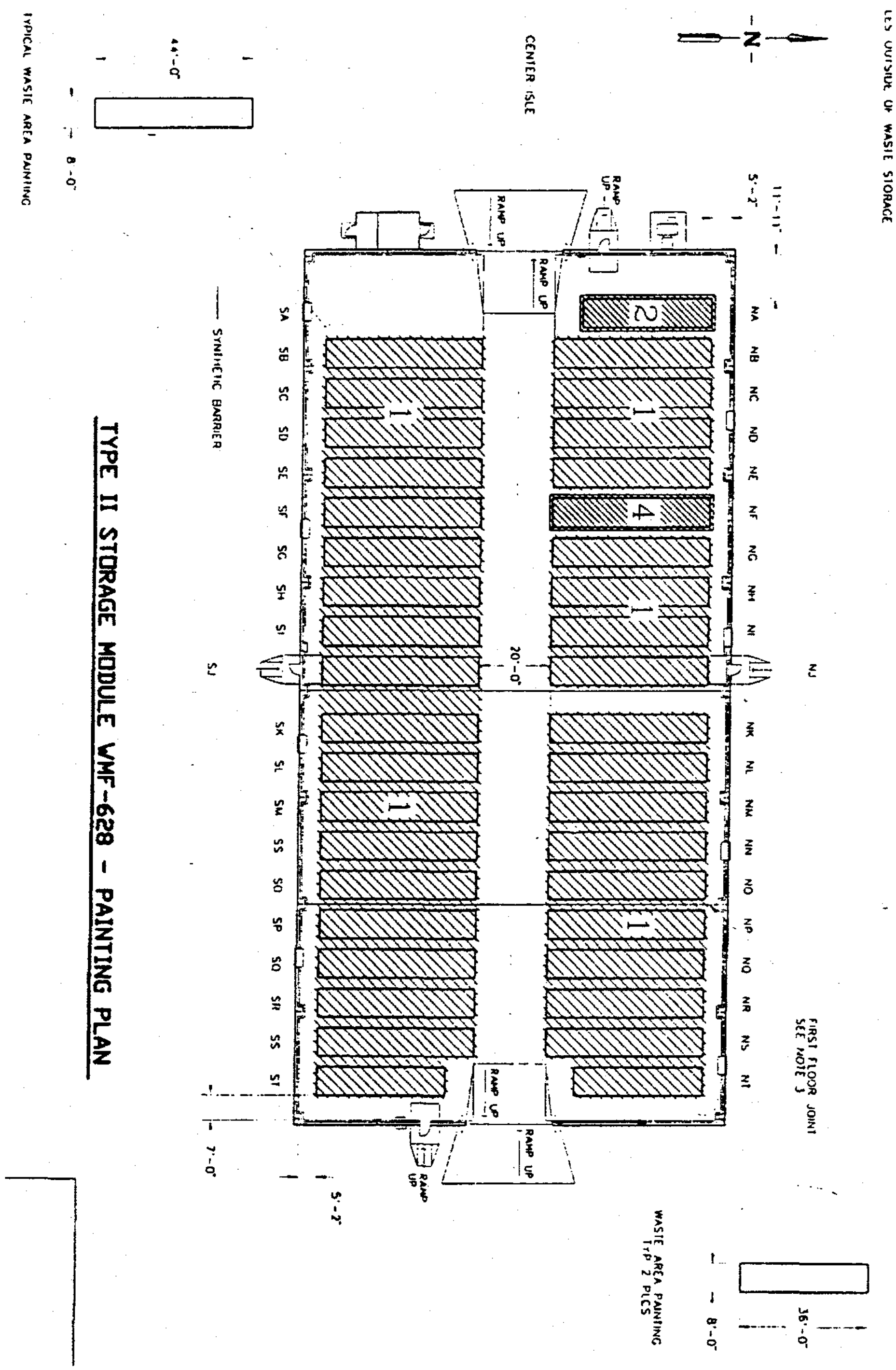

Figure 5-12. Building 628 configuration.

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.

4.4.3.2 Vehicle and Supporting Equipment

A reduced equipment set was taken to the RWMC site, as the goal was system installation with only minor 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

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 and support work must address the issues of hardware and software licensing for the development software both on the vehicle and for the operator workstation.

4.4.3.3 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.

5. CONCLUSIONS

The major goals of the third phase of the IMSS program was the evaluation and validation of the vehicle system in operational environments. The three specific parts to this process were the field trial activities at the FEMP site in Fernald, Ohio, the preparation and vehicle upgrade phase in Denver, and the installation activities at the INEL site. Each of these operations provided insights both into the operational characteristics of the vehicle as well as the way in which the inspection process could be enhanced for the safety of the inspectors and for the consistency of the inspection process. The wide variability in environmental conditions, especially temperature, presented an important means to evaluate the behavior of the vehicle subsystems and explore ways to make its operation more robust.

The most important conclusions from the Fernald field trial were

- The need for enhancements to the navigation subsystem for large facilities
- The need for enhancements to the navigation subsystem for varying row alignment
- The potential for integration of the ABCD inspection process onto the vehicle
- The need for enhancements for the operator workstation to improve usability

The most important conclusions from the Idaho installation activities

- Remote operation of the vehicle is established and provides a workable method for the INEL operators to use the vehicle from the Administration Building (658)
- A four high mast system is mechanically stable and provides visual inspection capability for the five high drum stacking arrangement at INEL
- Low temperature operation requires modification to vehicle operation procedures and potentially more robust storage hardware in the case of the SCSI disk
- Continuous vehicle operation is acceptable and enhances low temperature operation
- The radio ethernet system can be successfully adapted to a more difficult transmission environment

The next step in the evolution of the IMSS system is the evaluation of the system in the installed environment at INEL with feedback from the operators on both ease of use of the system as well as system performance. This information can then be used to make further enhancements to the current vehicle system and point out improvements that can be integrated into future generations of the vehicle.

6. REFERENCES

[IMSS Phase 1] "Intelligent Mobile Sensor System for Drum Monitoring", Topical Report, 1992.

[IMSS Phase 2] "Intelligent Mobile Sensor System for Drum Inspection and Monitoring", Topical Report, 1996.

[ABCD Phase 1] "Automated Baseline Change Detection Inspection System", Topical Report, 1996.

Appendix C

ABCD Phase 1 Topical Report

PHASE 1 TOPICAL REPORT

FOR PHASE 1 ENDING 20 FEBRUARY 1996
December 14, 1995

Automated Baseline Change Detection

Work Performed Under Contract:
DE-AR21-94MC31191

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(*) NOTE: Before the merger of Lockheed Corporation and Martin Marietta Corporation, the legal name of the contractor was Lockheed Missiles & Space Company, Inc. or LMSC. The legal name is unchanged but the complete legal name is Lockheed Missiles & Space Company, Inc., subsidiary of Lockheed Corporation, A Lockheed Martin Company. The public name is Lockheed Martin Missiles & Space or LMMS. The legal name and its abbreviation, LMSC, is generally used in this report.

ABCD Phase 1 Executive Summary

The Automated Baseline Change Detection (ABCD) project is supported by the DOE Morgantown Energy Technology Center (METC) as part of its ER&WM cross-cutting technology program in robotics.

Phase 1 of the Automated Baseline Change Detection project is summarized in this topical report. Project objectives and accomplishments are presented followed by the organization of the report.

ABCD Phase 1 Objectives

The primary objective of this project is to apply robotic and optical sensor technology to the operational inspection of mixed toxic and radioactive waste stored in barrels, using Automated Baseline Change Detection (ABCD), based on image subtraction.

Absolute change detection is based on detecting any visible physical changes, regardless of cause, between a current inspection image of a barrel and an archived baseline image of the same barrel. Thus, in addition to rust, the ABCD system can also detect corrosion, leaks, dents, and bulges. The ABCD approach and method rely on precise camera positioning and repositioning relative to the barrel and on feature recognition in images.

In support of this primary objective, there are secondary objectives to determine DOE operational inspection requirements and DOE system fielding requirements. The Phase 1 Statement of Work (SOW) is given in Section 1.1; the Phase 1 Work Breakdown Structure (WBS) is given in Section 1.2.

ABCD Phase 1 Accomplishments

The ABCD project met all of its Phase 1 objectives and also early (Phase 2) determination of the initial robotics platform for a fielded system. The criteria of change detection were determined in Task 1 and demonstrated in Task 2 as being suitable for operational utility. In Task 3, the ABCD system was deployed on another DOE robotic platform and successfully used to inspect a realistic array of waste barrels. DOE operational inspection criteria were determined in Task 4. Task 5, through integration of the ABCD system with the Intelligent Mobile Sensor System (IMSS), identified the significant requirements for specifying and integrating the ABCD system in a field system. (The IMSS project is also supported by the DOE METC.) Project management was Task 6. Phase 1 of the ABCD project was completed under budget, but completion was delayed to accommodate the integration of ABCD and IMSS, a very cost-effective consequence of the merger of Lockheed and Martin Marietta during the period of performance.

Report Organization

This topical report is organized into the same major section as the monthly status reports. It is also a self-contained report. Section 1 presents the formal objectives and work organization. Sections 2 and 3 present the chronology of critical milestones and events. Section 4 is a synopsis of accomplishments presented in Section 4 of the monthly status reports. Section 5 is a compendium of technical issues presented in Section 5 of monthly status reports. Sections 6 and 7 present the status at the end of Phase 1 and plans regarding Phase 2, respectively. Section 8 contains five attachments, one summarizing the technical results of each of the five tasks in the WBS.

The report is presented in the following sections:

Note on Nomenclature

For consistency the contractor abbreviation LMSC is used in this report. (See footnote on cover page.) Also for consistency, ABCD is used for Automated Baseline Change Detection, rather than just BCD.

1.0 Formal Objectives

1.1 Statement of Work

1.1.A. Objective

The objective of this effort is to apply robotic and optical sensor technology to the operational inspection of mixed toxic and radioactive waste stored in barrels.

1.1.B. Scope of Work

The work shall be performed in two phases with Phase 2 being optional. Phase 1 shall establish, through analysis and demonstration, the viability of the technology to the DOE waste management operational environment. The primary end results of the Phase 1 effort shall be the laboratory demonstration and delivery of the deployable prototype robotic, mobile, sensor system for the automated inspection of warehoused barrels containing mixed waste. Phase 2 will produce and operationally test a freely autonomous waste barrel inspection at a DOE site. The Phase 2 mobile field system shall integrate the ABCD sensor with an autonomous mobile platform in a manner which satisfies DOE operational and regulatory requirements for automated waste barrel inspection.

1.1.C. Tasks To Be Performed

TASK 1. CHANGE-DETECTION PERFORMANCE CRITERIA DETERMINATION

The contractor shall review options for attaching markers on waste barrels. The existing Kinetic Sciences, Inc. Eagle Eye™ marker will be redesigned as an adhesive label which will partially wrap around the curved surface of the drum. The optimum marker size and barrel identification number encoding scheme shall be specified.

The contractor shall determine expected performance criteria for a change detection system based on image subtraction by experimentally determining the following data: (1) the static sensor limits of barrel identification accuracy, (2) the limits of spatial resolution for detecting changes, (3) the limits in image contrast for detecting changes, and (4) limits of stability with changes in the change-detection sensor system components, such as cameras and lights.

The contractor shall prepare documentation describing the recommended marker, change detection, and autonomous camera performance requirements established for this project. The documentation shall be forwarded to DOE for review and comment.

TASK 2. CHANGE-DETECTION APPLICATION SYSTEM VERIFICATION

The contractor shall purchase, assemble, test, install and verify the required computer hardware and software (including the Eagle Eye™ vision system) for the automated Baseline Change Detection Application sensor system. This should include implementing image subtraction software suitable for change detection in subtracted images.

The contractor shall adapt the existing R2X robot testbed to use a change-detection video camera on a manipulator to iteratively reposition the camera until a predetermined pose of an Eagle Eye™ marker is obtained within specified limits. The R2X robot shall therefore be integrated with the Eagle Eye™ change-detection system.

The contractor shall prepare a test plan for DOE review and comment, for a test of the Change-Detection Application System to ensure that it meets its performance criteria as determined in Task 1. A test will be performed at the Lockheed laboratories showing that the R2X robot testbed is able to center a barrel marker on a barrel, determine the identification of the barrel, and then collect a reference image and barrel pose in the field of view of the change-detection camera. The barrel and/or a fixed joint of the R2X manipulator shall be able to arbitrarily move, with the camera repositioned to obtain the same pose and the same data collected, and change detection, if any, determined. The results obtained shall be compared with the performance criteria of Task 1.

TASK 3. CHANGE-DETECTION DEPLOYMENT SYSTEM PROTOTYPE VERIFICATION

The contractor shall continually monitor and coordinate with the DOE to ensure that the change-detection capabilities being developed are in line with current DOE requirements with respect to warehoused barrels.

The contractor shall update and complete the full design of the deployment-system hardware, and then fabricate, assemble, and test the unit; this shall include implementing and interfacing the identification, image processing, and imaging subtraction software and hardware for integration into the deployment system.

The contractor shall also assemble, implement, and test the Deployment System Camera-Position subsystem. This subsystem shall be integrated with the Deployment System Change-Detection to achieve a non-mobile Deployment System.

The contractor shall implement the Change-Detection Deployment System on a mobile navigation platform. The contractor shall test the mobile Change-Detection Deployment System in the laboratory to ensure that it meets it performance criteria for at least a 3x3 array of barrels (3 high by 3 wide). The test will include (1) obtaining and archiving barrel identifications and associated reference poses and images, and (2) autonomous inspection of the barrel array, displaying details of discovered changes.

TASK 4. CHANGE-DETECTION FIELD SYSTEM COMPATIBILITY VERIFICATION

The contractor shall assess the capabilities of the Change-Detection Deployment System to meet DOE compatibility requirements in the following areas: (1) site operations, (2) mobile platforms, and (3) regulatory compliance, by collecting relevant information available at the time scheduled for this task. The contractor shall ensure that the deliverable ABCD sensor system prototype is designed to easily interface with existing DOE or commercial navigation platforms using the Generic Intelligent System Control (GISC) protocols and software.

TASK 5. FIELD SYSTEM DEFINITION

The contractor shall define the operational requirements and develop a design concept for a Change-Detection Field System consistent with requirements identified in previous tasks. This system shall include, but not be limited to, the Change-Detection sensor, an autonomous mobile platform, integration with other sensors as required, a base-station with full inspection data processing and analysis, facilities for near-continuous mobile-platform power, backup, and inspection, and operator interface with remote monitoring and control.

The contractor shall perform preliminary trade-off studies of the design concept, and determine a cost estimate for a Change-Detection Field System consistent with previous tasks.

The contractor shall prepare and submit for review and comment a Topical Report summarizing the results of this phase at least 60 days before completion of the Phase 1 efforts. The DOE will provide written approval or suggest changes within thirty (30) days after receipt of the draft topical report.

Note: See Article B.010 for specific instructions regarding exercise of the Phase 2 activities. The contractor shall initiate Phase 2 activities only after it has received from the DOE Contracting Officer a unilateral modification authorizing them to proceed.

Should the DOE decide <u>not</u> to exercise the Phase 2 option, the Phase 1 Topical Report will be revised to become the Final Report. The contractor shall have an additional 30 days to provide a draft Final Report. The DOE will provide its comments within 30 days after submission of the draft Final Report. The contractor will then have 30 days to submit the Final Report.

TASK 6. PROJECT MANAGEMENT

The contractor shall manage the cost, schedule and technical elements of the Phase 1 effort. This task shall include project planning, oversight and reporting to the government, including subcontract management, if applicable.

The contractor shall prepare and submit reports in accordance with the Reporting Requirements Checklist and as applicable and described in the Section D, DELIVERABLES. The contractor shall prepare and present briefings to the DOE as applicable and described in Section E, BRIEFINGS.

Optional Phase 2 - Change-Detection Field System

TASK 7. INFORMATION REQUIRED FOR THE NATIONAL ENVIRONMENTAL POLICY ACT

The contractor shall prepare a draft report which provides the environmental information described in Attachment A2, "Required Information for the National Environmental Policy Act (NEPA)". This information will be used by the DOE to prepare the appropriate level of NEPA documentation for Phase 2 of the project. This draft report shall be submitted to the COR within sixty (60) days after contract award. DOE shall review the report and advise the contractor of the acceptability of the report or the need for additional information within thirty (30) days. The contractor shall submit a final report within two weeks of notice of acceptability of the draft report.

Until the NEPA review and approval process is completed the contractor shall take no action that would have an adverse impact on the environment or limit the choice of reasonable alternatives to the proposed action. The contractor is not precluded from planning, developing preliminary design, or performing other work necessary to support an application for Federal, State, or local permits.

TASK 8. FIELD TEST AND EVALUATION

The contractor shall build and integrate a field system prototype of the Change-Detection System to include an operational test and evaluation of an autonomous full function system at a DOE site. Prior to proceeding with this task however, the contractor shall prepare a test plan and forward it to DOE for review and comment.

TASK 9. PROJECT MANAGEMENT

The contractor shall manage the cost, schedule and technical elements of the Phase 2 effort. This task shall include project planning, oversight and reporting to the government, including subcontract management, if applicable.

The contractor shall prepare and submit reports in accordance with the Reporting Requirements Checklist and as applicable and described in the Section D, DELIVERABLES. The contractor shall prepare and present briefings to the DOE as applicable and described in Section E, BRIEFINGS.

1.1.D. Deliverables

The reports shall be submitted in accordance with the attached Reporting Requirements Checklist. The contractor shall submit the following, referred to in the Statement of Work:

a. Draft and final NEPA Report, described in Task 7.
b. Performance Criterion documentation described under Task 1.
c. Test Plan required under Task 2.
d. Phase 1 Topical Report described in Task 5.
e. The complete ABCD deployment sensor system hardware and software.
f. BCD sensor system demonstration and application videotapes.
g. Operation manuals.

1.1.E. Briefings

The contractor shall prepare detailed briefings for presentation to the DOE in Morgantown, West Virginia. The briefings shall be given by the contractor to explain the plans, progress and results of the technical effort. The first briefing shall be presented within 30 days after contract award. The final briefing shall be presented at least 60 days before contract expiration.

A briefing shall also be conducted at the conclusion of Phase 2 activities.

The contractor shall also attend the annual Office of Technology Development meeting generally held in Washington, DC.

1.2 Project Objective and Task Description:

1.2.1 Objective

The objective of this contract is to apply robotic and optical sensor technology to the operational inspection of mixed toxic and radioactive waste stored in barrels, using automated baseline change detection (BCD), based on image subtraction.

Phase 1

The Task 1 objective is to empirically determine performance criteria for the ABCD system.

The Task 2 objective is to integrate the ABCD vision system with a stationary robot to establish the functionality of the ABCD Application System.

The Task 3 objective is to integrate the ABCD vision system with a mobile robot to establish the functionality of the ABCD Deployment System.

The Task 4 objective is to establish the compatibility of the ABCD Deployment System with DOE and regulatory agency operational requirements.

The Task 5 objective is to complete a preliminary design and cost analysis of a ABCD Field System for field test and evaluation in Phase 2.

The Task 6 objective is to manage Phase 1 to meet reporting, deliverables, budget, and schedule requirements.

Phase 2

The Task 7 objective is complete the reports as given in "Required Information for the National Environmental Policy Act (NEPA)."

The Task 8 objective is to build, integrate, field test, and evaluate a ABCD Field System for an operational DOE site.

The Task 9 objective is to manage Phase 2 to meet reporting, deliverables, budget, and schedule requirements.

1.2.2 ABCD Phase 1 WBS Listing.

1. Change-Detection Performance Criteria Determination
    1.1. Id Marker Requirements Determination
    1.2. Change Detection Performance Criteria Determination
    1.3. Autonomous Camera Performance Criteria Determination
    1.4. Performance Criteria Review
2. Change-Detection Application System Verification
    2.1. Automated ABCD Computer System Purchase, Assemble, and Test
    2.2. ID Marker Production
    2.3. Application System Image Subtraction Test Implementation
    2.4. Application System Camera Implementation
    2.5. Application System Image & Positioning Integration
    2.6. Application System Criteria Testing
    2.7. Application System Review
3. Change-Detection Deployment System Verification
    3.1. Regulatory Agencies Presentations
    3.2. DOE Warehouse Operational Requirements Monitoring
    3.3. Deployment System Design Update, Purchase, Build, Assemble, and Test
    3.4. Deployment System Change-Detection Implementation
    3.5. Deployment System Camera-Positioning Implementation
    3.6. Deployment System Integration
    3.7. Deployment System and Mobile Base Implementation
    3.8. Deployment System Criteria Testing
    3.9. Deployment System and Final Review
4. Change-Detection ER&WM Field System Compatibility Verification
    4.1. DOE Site Operational Requirements Assessment
    4.2. Mobile Platform Assessment
    4.3. Regulatory Compliance Assessment
    4.4. ER&WM Compatibility Review
5. Phase 2 Field System Definition
    5.1. Change-Detection Field System Requirements Definition
    5.2. Change-Detection Field System Design Concept Development
    5.3. Change-Detection Field System Cost Determination
    5.4. Change-Detection Field System Requirements Review
6. Phase 1 Project Management

2.0 Major Milestones Status

Sub-task	Primary Task Description	Baseline	Revised	Actual	Reason for Variance
	DOE Kickoff	10/21/94	10/27/94	10/27/94	Schedule conflicts
1.4	Performance Criteria Review	12/15/94		12/15/94	
2.7	Application Review	03/21/95	5/12/95	5/12/95	Light control issues
3.1	Regulatory Agencies Presentations	04/04/95	11/30/95 12/07/95	11/30/95	Covered by DOE "Bake-off" meetings
4.4	ER&WM Compatibility Review	05/02/95	11/30/95 12/07/95	11/30/95	Covered by DOE "Bake-off" Meeting
3.9	Deployment System and Project Final Review	09/05/95	12/12/95		Integration with IMSS
5.4	Field System Requirements Review	09/05/95	12/12/95	11/30/95 12/07/95	Defined by DOE "Bake-off" Meetings

3.0 Chronological Listing of Significant Events and accomplishments

Significant Events

Date	Description
09/21/94	Contract signed by DOE and LMSC.
09/29/94	Lockheed Missiles and Space Company (LMSC) internal Contract Kick-off Review Meeting
10/21/94	PI and LMSC contracts representative kickoff meeting with subcontractor, Kinetic Sciences, Inc. (KSI), at Vancouver, BC, to discuss and agree on contractual and technical issues.
10/27/94	PI and LMSC contracts representative kickoff meeting with DOE at Morgantown, WV. to discuss and agree on contractual issues and discuss technical approach.
11/16/94	Subcontract completed between LMSC and KSI.
12/15/94	KSI trip to LMSC for technical review of Task 1 work.
02/27/95	KSI trip to LMSC for Application System Image & Positioning Integration.
03/20/95	KSI trip to LMSC to continue integration and software refinement (2 wks)
03/31/95	Task 2 lighting problems understood and fixes begun,
03/31/95	Task 2 Test Plan draft revised.
04/20/95	Attend DOE Intelligent Mobile Sensor System (IMSS) Phase 2 Demonstration at Lockheed Martin Astronautics, Denver
05/12/95	DOE Task 2 Demonstration and review at Lockheed Missiles & Space Company, Inc., Palo Alto.
05/12/95	With DOE coordination, integration planning was started for the Automated Baseline Change Detection project (Lockheed Missiles & Space Company, Inc., Palo Alto) and the Intelligent Mobile Sensor System project (Lockheed Martin Astronautics, Denver).
06/25/95	Project approach revised for integration of ABCD and IMSS.
07/19/95	Multicompany agreement on integration activities
07/26/95	Intercompany Work Transfer Initiated for IMSS integration
08/10/95	Phase 1 no-cost, three-month time extension request submitted to DOE
10/02/95	Visited DOE Fernald barrel warehouse to determine operational requirements and "bake-off" environment.
10/03/95	Reported the ABCD project at the Environmental Technology Development Through Industry Partnership Meeting at METC, 3-5 October 1995.
10/22/95	Reported elements of the ABCD project at the IEEE International Conference on Systems, Man, and Cybernetics, Vancouver, BC, Canada.
11/27/95	Started integrated experiments with Intelligent Mobile Sensor System at Lockheed Martin Astronautics, Denver, CO
11/30/95	Attended the ARIES (Autonomous Robotic Inspection Experimental System Phase 2 demonstration at the University of South Carolina, SC.

11/30/95	Participated in the DOE barrel-inspection "bake-off" planning meeting at the University of South Carolina, SC.
12/07/95	Attended the SWAMI (Stored Waste Autonomous Mobile Inspector) System Phase 2 demonstration at the DOE Fernald Laboratory.
12/07/95	Participated in the DOE barrel-inspection "bake-off" planning meeting at the DOE Fernald Laboratory.

To Date Accomplishments

Date	Description
10/17/94	Management Plan submitted.
10/18/94	Cost Plan submitted.
10/24/94	Milestone Plan submitted.
11/16/94	Quality Assurance Plan and Revised Management Plan submitted.
11/30/94	Camera and marker label parameters determination completed.
12/15/94	Task 1 objectives accomplished and Task 1 reviewed and completed.
04/30/95	Task 2 verification of Task 1 performance criteria.
05/12/95	Task 2 Demonstration and Review for DOE
06/25/95	Project approach revised
06/30/95	Tiling algorithm for image registration completed
08/31/95	New software installed, tiling algorithms successfully tested
09/30/95	Change-patterns created and tested for IMSS repositioning
10/30/95	New tiling registration based on pose marker implemented.
11/20/95	Implemented new image subtraction algorithms with automatic specular reflection detection.
11/24/95	Completed experiments in Palo Alto using IMSS instrument pod.
11/30/95	Attended the ARIES (Autonomous Robotic Inspection Experimental System) Phase 2 demonstration at the University of South Carolina, SC.
11/30/95	Collected DOE operational requirements information (Task 4) at the DOE barrel-inspection meeting at the University of South Carolina, SC.
12/01/95	Completed experiments in IMSS laboratory in Denver using IMSS platform to collect baseline and inspection images.
12/07/95	Collected DOE operational requirements information (Task 4) at the DOE barrel-inspection meeting at the DOE Fernald Laboratory.
12/08/95	Completed electronic transfer of images from Denver to Palo Alto and began final analysis of ABCD Task 3 capabilities.

4.0 Phase 1 Accomplishments

ABCD Phase 1 accomplishments are listed in Work Breakdown Structure (WBS) order, which is the same as tasks and subtasks.

WBS Element / Task 1.0 Change-Detection Performance Criteria Determination

Change-detection performance criteria were determined. In addition, two important models were also developed. The first is a spread-sheet implementation of the system optics. The second is an algorithm and procedure for self calibration of the camera, allowing component changes as needed. When better lenses and marker production methods are used in Task 2 and Phase 2, these models will allow their use consistent with Task 1 criteria. The performance criteria are summarized in Section 5 and Attachment 1.

WBS Element / Subtask 1.1 Id Marker Requirements Determination

The optical geometry associated with drum label viewing was analyzed to assess the critical parameters that determine what the size of the label and how the Eagle Eye™ marker patterns should be arranged on the label. It is important for the label to obscure as little of the drum surface as possible but also important that the label be large enough to permit accurate repositioning of the camera using the Eagle Eye™ vision system. The drum labels are the means by which drums are uniquely identified and also are the optical targets upon which camera positioning is based.

The choice of lens focal length was revisited. The choice of focal length determines directly how far back from a drum the camera needs to be to see the entire drum. Earlier analysis indicated a very wide angle lens was needed, and this was a concern in terms of price, availability, and the amount of distortion that might need to be accommodated. With the camera specifications now firm this issue was revisited and a more commonly available (longer focal length) lens has been selected.

The dimensions of the barrel identification and pose markers were determined. Marker values are summarized in Section 5 and Attachment 1.

WBS Element / Subtask 1.2 Change Detection Performance Criteria Determination

Change detection criteria were determined for a spot size of 1/4 inch (0.64 cm). The criteria are presented in Section 5 and Attachment 1.

WBS Element / Subtask 1.3 Autonomous Camera Performance Criteria Determination

Analysis of the camera position accuracy made progress in the areas of calibration accuracy and in characterizing the nature of positioning errors. The positioning accuracy is an important factor in determining how successfully we can compare two images of the same drum captured on different visits to the drum.

The self-calibration algorithm and software were completed; this is a significant, enhanced capability beyond original plans. The focal length of the current camera lens was determined empirically using the self-calibration system. Positioning accuracy of the camera for repeatable pose determination was determined. The camera performance criteria are presented in Section 5 and Attachment 1.

WBS Element / Subtask 1.4 Performance Criteria Review

On 15 December 1994, Dr. Jeremy Wilson of KSI met in Palo Alto with Dr. Berardo, and David Van Vactor of LMSC, to review progress and status of work done in WBS Elements / Subtasks 1.1, 1.2, and 1.3. The results are presented in Section 5 and Attachment 1.

WBS Element / Task 2.0 Change-Detection Application System Verification

Given the performance criteria determined in Task 1, Task 2 verified that they could be achieved for waste-barrels in laboratory conditions. To complete Task 2, both hardware and software was purchased, integrated, and tested.

WBS Element / Subtask 2.1 Automated ABCD Computer System Purchase, Assemble, and Test

Hardware components for the Application System were ordered by KSI (the major components of this being the Power Macintosh 8100/80, the IMAXX color frame grabber, and the Hitachi 3-CCD color camera) and received. KSI started testing the color frame grabber in preparation for extending the Eagle Eye™ marker tracking software to interface with this model of frame grabber.

We encountered a mechanical problem with mounting the existing 4.2mm wide-angle lens on this camera (the lens was not fully compliant with the C-mount standard), and so choices for an alternative lens were investigated. Because of this problem , the use of the color camera was postponed until Task 3 and in the mean time a black and white camera was used. The computer hardware and light track (used for illuminating the drum) were received at Lockheed for integration with the R2X robot testbed.

The 3 CCD Hitachi color camera was delivered to Lockheed for use in the Task 2 testing. A high quality 5.7 mm lens suitable for this camera was also purchased and delivered.

The 3 CCD Hitachi color camera published specifications were experimentally determined to be in error. The vendor researched the problem and determined that indeed there was a mistake. The primary result is that the effective focal length of the camera and lens is over 6 mm. This in turn requires that the camera be more than an aisle width away from a barrel in order to see the entire barrel in one view. Returning the lens and camera to the vendors was not done because the superior distortion reduction of this system has utility for multiview inspections.

Section 5 and Attachment 2 discuss the camera and lens issues further.

WBS Element / Subtask 2.2 ID Marker Production

The production of a number of drum labels for use by Lockheed R&DD for testing purposes was postponed until a design for the illumination calibration portion of the label was completed. This design depends on the procedure for illumination calibration that is being developed under Subtask 2.3. The labels were not needed by Lockheed R&DD until later so there was no overall schedule impact.

A set of fourteen drum labels were prepared. Twelve of these were received at Lockheed, and two were kept for use by KSI. The label includes a new design for the intensity calibration grid. This grid is used by the change-detection software to adjust for variations in illumination between the baseline image of a drum and a new image of a drum.

The accuracy of Eagle Eye's pose information is weak along the drum "tilt" axis (this was a known property of the label design). It was found that the R2X robot also had lower than expected resolution on this axis. As an experiment to improve the accuracy of the pose data, a three face version of the drum label was produced in which the faces were arranged in a T-shape, making the label about twice as high. The disadvantage with this label is its large size, obscuring more of the drum surface. We believe that a more sophisticated approach to image registration will reduce the need for such a wide label.

WBS Element / Subtask 2.3 Application System Image Subtraction Test Implementation

Work began on developing the change detection software, based on using IPlab™ (an image processing application for the Macintosh from Signal Analytics), and an early version of the change detection procedure was implemented. An investigation of how to best compensate for changes in illumination which is important for reducing false indications of change was started. This involves developing a procedure for calibrating the CCD camera's light intensity response characteristics. Improvements were made in the speed and robustness of KSI's Opti-Cal automatic lens & camera calibration software and KSI's Eagle Eye™ marker tracking software, and these improvements are described in the next section of this report. The problem of integrating and coordinating the various components of the ABCD system were addresses.

IPLab scripts were developed for the Application System. These scripts perform the image processing necessary for change detection, including adjusting for ambient illumination, adjusting for changes in the light output from the robots illumination system, and calculating statistics for the detected changes (such as their location, size, and mean intensity).

The change detection algorithm was found to be too sensitive to specular reflections from the drum surface, with the result that these specular reflections were often detected as changes. A masking technique was implemented so that the small areas of the drum with specular reflections were excluded from the change detection. Work was started automating the generation of the mask.

Another unexpected difficulty with change detection was achieving accurate image registration over the entire image. We found that simple translational registration does not cope adequately with imaging properties such as lens distortion and image rotation. As a short term work around, the positioning tolerances for the R2X arm were increased. The longer term solution is to take a more sophisticated approach to image registration. Section 5 provides further detail on these two problems.

The change detection algorithm was improved so that it is less sensitive to camera positioning errors. Subpixel image registration was implemented and tested. Also tested (but not implemented) was the concept of breaking the image into smaller 'tiles' and performing local image registration on each tile. The test results show that the method has real potential. KSI provided Lockheed with a draft proposal for addressing the problems of image misregistration due to camera position errors based on the combination of subpixel registration and image tiling. Section 5 presents the test results.

Work has continued on improving the change detection algorithm so that it is less sensitive to camera positioning errors. Early results were promising on improving the change detection algorithm so that it is less sensitive to camera positioning errors, with a significant reduction in false positives due to misregistration. A small amount of experimentation was also done on an alternative light source designed to reduce specular reflections and to illuminate the drum uniformly. These results are reported in Section 5.

<u>WBS Element / Subtask 2.4 Application System Camera Implementation</u>

The R2X robot testbed was adapted for the ABCD Application System Verification. A CCD camera was mounted on the 7-DOF manipulator tool plate. The light system used by KSI in Task 1 was also mounted on the tool plate so that camera and lights move together. Camera and ethernet communication lines were routed for integration with the image and positioning system. The R2X motion control process was modified to receive camera-relative label-center offsets from the image and positioning system and to use these offsets with the existing R2X manipulator geometry and an inverse kinematic solver to generate corrective motions to center the camera on the barrel label.

The curvature of the drum and the use of a wide angle lens make it difficult to achieve even illumination of the drum. A new lighting system was developed to provide better illumination. Section 5 provides further detail on the design of the illumination.

WBS Element / Subtask 2.5 Application System Image & Positioning Integration

The system architecture for integrating the various image processing components into the Application System was implemented. (This architecture is described in Section 5). Eagle Eye™ was extended so that it can respond to commands from another program to determine label pose and to save the current image. KSI delivered the image-processing hardware and software to Lockheed and Jeremy Wilson of KSI spent a week at the Palo Alto Automation and Robotics Laboratory collaborating on system integration. During this task, each of the software components on the Macintosh were tested in isolation, and then under the control of the R2X computers via the local Ethernet network. The communications protocol between the R2X control system and the Macintosh were defined, implemented, and tested.

The Image Processing Manager (IPM) was reworked to improve robustness and the messaging protocol extended so that more flexible control of the Image Processing Workstation was possible. Eagle Eye™ was modified to enable control of continuous tracking in order to improve the response time for obtaining label pose data.

The robot control system was expanded and refined, mainly to reduce the time for change detection. Protocols were added to receive the latest pose estimate from marker tracking by the IPM. Tests were done with the R2X command protocols to determine that R2X commands could be updated at tracking rates. Actuator gains were adjusted to eliminate resonances due to the increased moments of inertia from larger lighting arrays that are linked to and moved with the camera.

WBS Element / Subtask 2.6 Application System Criteria Testing

Preliminary tests of camera centering were quite successful. This involved automatically centering the camera on the barrel label and sensing the difference between desired and actual camera positions. Typically these differences were about half the allowed tolerance, indicating that, on the basis of pose reproducibility, baseline change detection is practical.

During Application System integration (Subtask 2.5, above) it was determined that the image processing system was very sensitive to lighting conditions. Briefly, the principal problem is specular reflection of the light sources off the curved surfaces of the drums. This can either cause saturation of the CCD camera or, if the light intensity is reduced, lost of sufficient detail in the barrel label for reliable pose determination. Several exploratory experiments were done and remedial actions were investigated.

Task 2 verification and testing of Task 1 performance criteria was delayed. Problems with reliable change detection did not warrant comprehensive testing until uniform lighting and specular reflection issues are resolved.

The testing was done with semiglossy black barrels using a black-on-white label with Eagle Eye™ markers. Thus the full range of the CCD camera is involved in the tests, from completely black to completely white. This is more challenging than experienced in Task 1 or anticipated in Task 2. Yet, as these issues are resolved, the greater the feasibility for reliable field operations with the full range of real barrels.

It was experimentally determined that the Eagle Eye™ pose-determination subsystem and the R2X camera positioning subsystem each had more than adequate resolution to meet Task 1 criteria. The resolutions are about equal and the combined resolution is better than required by about a factor of two.

However, saturation limits and light intensity gradients, especially in regions of specular reflection, limit the reliability of change detection. More uniform lighting and elimination of specular reflection regions by predefined masks do allow repeatable and meaningful change detection.

The test plan was revised to establish "True-Positive / True-Negative" reliability estimates. This relies on predicting detected changes for various dot patterns of different sizes and contrasts. Test patterns are being refined and the requirements of an automated statistical analyzer are established.

Although both the Eagle Eye™ and R2X systems individually and jointly meet the Task 1 performance criteria for repeatability, high-gradient lighting variations often result in a high false-positive rates.

A new set of test patterns was generated that test the limits of change detection as a function of size, contrast, polarity (dark on light or light on dark), and location on the barrel. The test plan is being updated to reflect actual tests.

Many tests were done to try to balance the light intensity over the barrel. The number of lights, light orientation, light diffusers, light polarizers, filament masks, absolute light intensity, and camera aperture were varied so that the high-contrast barrel label and the far-off-center black portions of the barrel could both be imaged for pose and true-positive change determination. In other words, there needs to be enough light to see small changes in black areas but still not saturate the camera in white regions.

A reasonably adequate configuration with four lights was selected. However, specular reflections needed masks (excluded) regions in the change-detection processing.

To improve the system throughput the tracking capability of Eagle Eye™ was made available to the inspection control subsystem by expanding the existing communication protocol.

When the system was reasonably well understood and stable, experiments were designed to verify the capability of the system to meet Task 1 performance criteria. The experiments were completed and the results analyzed. They are also presented in this report as Attachment 2.

WBS Element / Subtask 2.7 Application System Review

The Task 2 Application System Review by DOE was held at Lockheed's Palo Alto lab on May 12th. Attending were the DOE Contracting Officer Representatives for both the ABCD (Automated Baseline Change Detection project, Clifford Carpenter, and the IMSS (Intelligent Mobile Sensor System) project, Kelly Pearce. Since Lockheed and Martin Marietta merged, both of these projects were now at Lockheed Martin companies. The IMSS Program Manager, Eric Byler, also attended, as well as Lawrence Livermore National Laboratory representatives of the DOE SWAMI (Stored Waste Autonomous Mobile Inspector) project at Savanna River. Subcontractor representatives were Guy Immega, Program Manager, and Jeremy Wilson, Principal Investigator. The ABCD contractor team included Peter Berardo, Program Manager and Principal Investigator, and Carl Adams and Bill Dickson, Project Engineers.

The review and demonstrations proceeded as planned. Three main conclusions were reached.

First, the difficulties of lighting are common to all the DOE projects. The performance criteria achieved by this project for two images are as good as any single images for other projects. That is, repositioning of the ABCD sensor was adequate to determine changes except were limited by the physics of the optics and geometry of aisles and barrels.

The second main conclusion is that the ABCD absolute change-detection capability is a desirable and often necessary first step in the overall inspection process. Other projects are pursuing image understanding and defect recognition. For example, red rust detection is fairly robust. However, there are other progressive defects, which will not be similarly recognized for some time, such as small volume dents and bulges or changing appearance. Thus, absolute change detection is a valuable precursor to image understanding for focusing attention and probably the only way of detecting some critical changes. Therefore, integration of ABCD capabilities into all of the other DOE barrel inspection projects is a common objective.

The third main conclusion is that since their merger, Lockheed Martin in Denver with the IMSS project and Lockheed Martin in Palo Alto with the ABCD project should closely collaborate and integrate the two projects. With unrestricted intercompany transfer of labor and data, this should improve the cost-effectiveness of both projects. Integration plans were started immediately.

An extended telephone conference was held with the project team (LMSC: Peter Berardo, Carl Adams, Bill Dickson, and David Van Vactor; KSI: Guy Immega, Jeremy Wilson, and Gloria Chow) to discuss the replanning of Task 3 and Phase 2 to accommodate the new objective of IMSS integration. The conclusions are presented in Section 5.

WBS Element Task 3.0 Change-Detection Deployment System Verification

Task 3.0 originally planned to use the existing Lockheed Nomadic robot, Argus, as a testbed for mobile-robot verification of change detection. A camera-positioning device was to be designed and interfaced with Argus. Discussions with Nomadic resulted in some new options which could both reduce the cost and provide a better deliverable to the DOE. Performance tests by Nomadic were to determine their robot positioning precision. Section 5 discusses these issues in more detail.

With the opportunity and DOE direction to integrate ABCD with the IMSS project, the scope and character of this task changed. The final approach is presented in Section 5. Generally, more effort was in image registration, rather than hardware implementation. This is reflected in the minimal work done in Subtask 3.3 to build an ABCD deployment system and the extra work done in Subtask 3.4 to handle ABCD image registration and subtraction for smaller IMSS repositioning accuracy.

WBS Element / Subtask 3.1 Regulatory Agencies Presentations

Subtask 3.1 was effectively superseded by DOE METC initiatives to consult warehouse operators at DOE laboratories to determine their requirements, both those imposed by regulatory agencies and those of an operational character. DOE contractors developing robotic systems for warehouse inspections, including this ABCD project, participated in this effort. The results for ABCD are presented in this section, Task 4.0.

WBS Element / Subtask 3.2 DOE Warehouse Operational Requirements Monitoring

Subtask 3.2 also was effectively superseded by DOE METC initiatives to consult warehouse operators at DOE laboratories to determine their requirements, both those imposed by regulatory agencies and those of an operational character. DOE contractors developing robotic systems for warehouse inspections, including this ABCD project, participated in this effort. The results for ABCD are presented in this section, Task 4.0.

WBS Element / Subtask 3.3 Deployment System Design Update, Purchase, Build, Assemble, and Test

Argus, the Nomadic robot testbed, was installed in the Automation and Robotics Laboratory, collocated with R2X. Preliminary testing of software links for remote commanding and monitoring of the autonomous robot was performed.

The Phase 2 demonstration and review of the DOE Intelligent Mobile Sensor System project with Lockheed Martin Astronautics in Denver was attended 20-21 April. Initial concepts were discussed as to how the ABCD system could be integrated with the IMSS mobile platform and data collection system. This integration was initiated and incorporated into ABCD plans. Integration with IMSS eliminated the need for building another sensor actuator for ABCD with considerable savings to the DOE. It also directs early integration of the ABCD system with an on-going DOE mobile-platform project.

With the opportunity and DOE direction to integrate ABCD with the IMSS project, the scope and character of this task changed. The final approach is presented in Section 5. Generally, more effort was in image registration, rather than hardware implementation. This is reflected in the minimal work done in Subtask 3.3 to build an ABCD deployment system and the extra work done in Subtask 3.4 to handle ABCD image registration and subtraction for smaller IMSS repositioning accuracy.

<u>WBS Element / Subtask 3.4 Deployment System Change-Detection Implementation</u>

With the opportunity and the DOE direction to integrate ABCD with the IMSS project, the scope and character of this task changed. The final approach is presented in Section 5. Generally, more effort was in image registration, rather than hardware implementation. This is reflected in the minimal work done in Subtask 3.3 to build an ABCD deployment system and the extra work done in Subtask 3.4 to handle ABCD image registration and subtraction for smaller IMSS repositioning accuracy.

Further testing of the tiling algorithm for image registration was done. Details are reported below in section 5. Tests were run using the R2X testbed and the images captured during the Subtask 2.6 testing. KSI provided LMSC a software update via the Internet.

The software extensions required for capturing color images from the color camera were implemented. These extensions were required to support the IMAXX-SC color frame grabber. A meeting was held with Prof. David Lowe of the University of British Columbia. Brief notes from this meeting are recorded below in Section 5. This new code was integrated into Eagle Eye™ and tested. the change detection scripts to process color images was updated.

At the LMSC Palo Alto lab the improved change detection algorithm was tested on the images captured during Task 2, and on new images. This approach used the full-image tiling algorithm for image registration. In support of this work there were a number of software updates and bug fixes: the updated IPLab scripts for change detection, an upgrade to Eagle Eye™, an updated Eagle Eye™ User's Guide, and enhancements to the IPM (Image Processing Manager) to improve ease of use.

Tests generally show a significant reduction in the number of false-positive changes. Because the new registration method should be less sensitive to camera-pitch repositioning, the tests were repeated with a smaller two-marker label, rather than the three marker label. However, additional changes are evident, perhaps related to light intensity calibration differences for the two different types of labels.

A literature search was conducted regarding the problem of identifying specular reflections.

Work continued at the LMSC Palo Alto lab on testing the improved change detection algorithm. Test patterns were created to test baseline and inspection image registration for repositioning offsets comparable to those expected for the IMSS platform (up to 2 cm). The critical registration area is the center of the images, which is used as a basis for registration in other areas of an image. Patterns and tests were designed to determine registration capabilities. Tests were conducted and registration capabilities were mostly as expected.

In support of this work KSI has provided a number of software updates and bug fixes. In particular it was found that both Eagle Eye™ and the IPLab change detection code required further work in order to be able to perform change detection for larger camera repositioning differences. These changes are also in support of the requirement to handle change detection on a small database of drums. Further details of the work on this task are described in Section 5.

Work continued on improving the robustness of the change detection software to errors in camera positioning and on preparing the change detection software for testing using the IMSS platform in the Denver lab. This is discussed in further detail in Section 5.

Carl Adams of LMSC tested the ABCD system with the IMSS instrument pod mounted on the R2X robotic testbed in Palo Alto. Problems with light intensity, intensity normalization, and specular reflection were consistent with previous experience and several enhancements were undertaken.

The change detection scripts and extensions were upgraded so that the label pose information from Eagle Eye™ was used to compute the image coordinates of the center of each intensity cell so that the label can appear anywhere in the image. The correlation processing (which registers the baseline and new images) also uses the label information so that correlation starts in an area where there is good texture (i.e. on the label). A technique for automatically computing a specular mask was implemented and preliminary testing performed. This method is based on comparing the ambient and fully illuminated images to detect bright reflections due to the robots lights that only appear in the fully illuminated image. The intensity calibration grid is an important element of this process. The mask generated from this process is then used during change detection to exclude the specular regions, because platform positioning errors can cause these specular regions to move and induce false detections of change.

Various changes were made to the Image Processing Manager (IPM) program to support batch processing of images captured by the IMSS platform.

The label design was revised to make the overall size smaller (obscuring less of the drum) and to bring the Eagle Eye™ face patterns on the label closer together so that they could be seen from both left and right cameras of an IMSS sensor suite. A set of 30 uniquely numbered adhesive labels were laid out and printed in preparation for the test at LMA (Denver).

Experimental results in Palo Alto with these software upgrades were quite satisfactory.

Further work developed various updates and enhancements to the change detection software to better deal with specular reflections and light intensity normalization. These additional enhancements were installed and successfully tested.

WBS Element / Subtask 3.5 Deployment System Camera-Positioning Implementation

During the initial integration with R2X, it was noted that Eagle Eye™ occasionally computed incorrect locations for the corners of the drum label, with the result that it would return an incorrect pose for the label. The cause of this problem was found (an algorithmic error) and the problem fixed.

Improvements were made to the Eagle Eye™ user interface, with tracking algorithm parameters now accessible in a dialog. The application is now able to read an image from a file (as an alternative to capturing a live image from a frame grabber), a function which is needed for post-processing of images (e.g. for testing the positioning repeatability of the IMSS platform).

Correspondence and discussions with Lockheed Martin Missiles & Space (LMSC, Palo Alto), Lockheed Martin Astronautics (LMA, Denver), and Kinetic Sciences, Inc. (KSI) were agreed upon with regard to testing the positioning repeatability of the IMSS platform using Eagle Eye, installing and testing part of the mast the IMSS system on the LMSC R2X testbed, and integration and demonstration of the ABCD system with the IMSS at Denver.

Progress on this task was slow while the start of the IMSS project's Phase 3 was held up. When IMSS Phase 3 was approved this work proceeded more rapidly. A new (smaller) drum label was designed, appropriate to the IMSS imaging configuration. Two sample labels and an Opti-CAL calibration target were sent to Eric Byler, IMSS Program Manager, so that sample images could be captured to verify the set up. Further details of the work on this task are described in Section 5.

Inspection images with KSI Eagle Eye™ markers were taken at Lockheed Martin Denver and shipped to KSI for analysis. KSI verified that the image file format used by the IMSS project could be correctly read using IPLab. The initial test used the IMSS platforms central black-and-white image cameras. However the results from these cameras were not satisfactory because they are defocused for use with the structured lighting system. We have switched to using the color cameras and tests with these are now proceeding. The purpose of these tests is to verify that we can calibrate the cameras using KSI's Opti-CAL program and to ensure that the Eagle Eye™ labels are visible from both the left and right side color cameras.

The IMSS sensor pod arrived at Lockheed Martin Palo Alto and was installed on the R2X testbed. Power and signal cabling was completed and tests begun when the revised tiling and intensity-normalization software was available.

Ray Rimey of LMA and Carl Adams of LMSC captured test images of the Opti-CAL calibration target using the IMSS sensor suites. These images identified a problem with Opti-CAL being too sensitive to pattern noise in the image. This problem was successfully addressed by enhancing the Opti-CAL user interface to allow the user to select an edge detection threshold above the level of this background noise.

The Eagle Eye™ software was modified to enable the camera calibration parameters to be loaded from a file under command of the Image Processing Manager (IPM) program. This function was added to support batch processing of imagery from the multiple cameras on the IMSS platform.

WBS Element / Subtask 3.6 Deployment System Integration

With the opportunity and DOE direction to integrate ABCD with the IMSS project, the scope and character of this task changed. The final approach is presented in Section 5. Generally, more effort was in image registration, rather than hardware implementation. This is reflected in the minimal work done in Subtask 3.3 to build an ABCD deployment system and the extra work done in Subtask 3.4 to handle ABCD image registration and subtraction for smaller IMSS repositioning accuracy.

WBS Element / Subtask 3.7 Deployment System and Mobile Base Implementation

With the opportunity and DOE direction to integrate ABCD with the IMSS project, the scope and character of this task changed. The final approach is presented in Section 5. Generally, more effort was in image registration, rather than hardware implementation. This is reflected in the minimal work done in Subtask 3.3 to build an ABCD deployment system and the extra work done in Subtask 3.4 to handle ABCD image registration and subtraction for smaller IMSS repositioning accuracy.

WBS Element / Subtask 3.8 Deployment System Criteria Testing

Carl Adams (LMSC, Palo Alto), Pete Berardo (LMSC, Palo Alto), and Jeremy Wilson (KSI, Vancouver) traveled to Denver to test the ABCD software in conjunction with the IMSS platform. Further details of this trip are described in Section 5.

The images for the IMSS (Intelligent Mobile Sensor System) platform and laboratory at Lockheed Martin Astronautics in Denver were electronically transferred to Palo Alto for change-detection analysis. The large image dataset gathered in the IMSS lab (LMA, Denver) required extensive review and systematic analysis of ABCD in a simulated warehouse with a variety of changes in barrel images. The last work item for KSI for Task 3 was the completion of some enhancements to the Image Processing Manager (IPM) software to make the large dataset easier to manage.

In the IMSS warehouse mockup the labels were placed on the barrels in arbitrary locations, as imagined would be done in real warehouse operations. But since the IMSS robot centers on the barrel and not the label, a good image of the label was not always obtained. In addition, image noise was common when the cameras were reinstalled on the IMSS platform after testing in Palo Alto.

These new problems were addressed and some images will not be analyzed. In operational practice, this would require some reinspections. In development, it indicates that real-time image analysis and possible real-time control of the robot platform position, camera aperture, and light intensity are highly desirable.

Attachment 3 presents a complete description of the ABCD imaging enhancements and imaging experiments that were completed to both validate the ABCD system and achieve initial integration with the IMSS system. These results validate the performance of the ABCD system when integrated on the IMSS mobile platform. First, individual cases for each defect type are presented to give a representative example of the system performance. Next, some statistics for the detection rate and false positive rate are determined for all of the multiple run data as a whole. Lastly, the IMSS repositioning performance data is presented.

Generally the results conform to the performance criteria established in Task 1 and verified in Task 2. The additional effort required for enhancements of the change-detection software provides an overall more robust system and earlier than planned integration with other DOE projects. However, the IMSS experiments clearly indicate several areas that need more work to improve overall ABCD/IMSS system robustness. These are in the areas of software integration and portability, lighting and camera-iris control, repositioning feedback to the IMSS platform, video noise, and processing time. These issues and Task3 conclusions are discussed in Attachment 3.

WBS Element / Subtask 3.9 Deployment System and Final Review

This Topical Report with a video tape of Task 3 Deployment System experiments, including final Deployment System test results and analyses, is the primary form of the Phase 1 review.

WBS Element / Task 4.0 Change-Detection ER&WM Field System Compatibility Verification

Task 4.0 was effectively accomplished by talking with Hanford representatives, visiting Fernald, and participating in DOE METC initiatives to consult warehouse operators at DOE laboratories to determine their requirements, both those imposed by regulatory agencies and those of an operational character. This direct DOE approach established uniform and realistic inspection and operational criteria for all DOE contractors developing robotic systems for warehouse inspections, including this ABCD project. With the strong initiative and leadership of the DOE CORs, the character and specifics of this task changed and achieved a cost-savings for the DOE. The results for ABCD are presented in Attachment A4.

WBS Element / Subtask 4.1 DOE Site Operational Requirements Assessment

Two people at the Hanford site were contacted to determine if we there had been any further developments in the operational requirements for automated drum inspection. We learned that OSHA (Occupational Safety Health Administration) had become involved in the process of defining requirements for the storage of the drums. Of particular interest was their reported requirement that the minimum aisle width be increased from 30" to 36" to conform with other safety standards for warehouses. This has an important impact for ABCD in the choice of lens for the camera because it means that the camera can be further away from a drum without touching a drum on the other side of the aisle. This means that the lens does not need to have such a wide field of view as we had originally thought, and the radial distortion will consequently be less.

At the American Nuclear Science conference in Monterey, California, Westinghouse Hanford Company representatives indicated that individual warehouses may contain as many as 12,000 barrels, rather than a maximum of 7,000. The barrels may be of three different sizes and may be stacked as many as four high. Additionally, it was envisioned that robotic inspection would only occur during "second and third shift". With about five hours of operation and three hours of charging per shift, the effective rate of barrel inspection needs to be about three barrels per minute, rather than about one and a half. Our original time line estimate was 18 seconds per barrel, so there is not much margin if such large warehouses and accompanying time restrictions prevail.

On behalf of ABCD, Dr. Peter Berardo visited the DOE Fernald laboratory to further determine operational barrel-warehousing requirements and procedures that could be of specific interest to ABCD. Eric Byler, IMSS Program Manager, also participated on behalf of IMSS. Practical integration of the ABCD and IMSS projects was facilitated by this visit. In addition, numerous photographs and video recordings of the warehouse were taken. Copies were distributed to all interested parties and serve to represent the range of actual barrel appearances. Some of the surprises were the overhang of 85-gallon barrels, different size barrels at different heights in the same vertical column, pallet offsets in the end of an aisle of barrels as a function of height, and the difference in height of metal versus wood pallets.

The SWAMI (Stored Waste Autonomous Mobile Inspector) robot was in the warehouse preparing for experiments. A test aisle of all 55-gallon barrels was configured to accommodate SWAMI and should be inspectable by IMSS with ABCD.

Berardo also attended the Phase 2 demonstration and review of the DOE Intelligent Mobile Sensor System project with Lockheed Martin Astronautics in Denver. The DOE

CORs for both the ABCD and IMSS projects led the attendees in defining a collective set of DOE site requirements. Rather than be collected independently by the ABCD project, there will be a subset of all DOE requirements that all barrel inspection projects can use as a common objective.

Berardo also attended the DOE barrel-inspection "bake-off" planning meeting at the University of South Carolina. Preliminary criteria, scheduling, and the role of ABCD were discussed.

Carl Adams, LMSC, and Guy Immega, participated in the DOE barrel-inspection "bake-off" planning meeting at the DOE Fernald Laboratory.

WBS Element / Subtask 4.2 Mobile Platform Assessment

Dr. Peter Berardo, LMSC, and Guy Immega, KSI, attended the Phase 2 demonstration and review of the DOE IMSS (Intelligent Mobile Sensor System) project with Lockheed Martin Astronautics in Denver.

Berardo, LMSC, also attended the ARIES (Autonomous Robotic Inspection Experimental System) Phase 2 demonstration at the University of South Carolina, SC.

Carl Adams, LMSC, and Guy Immega, KSI, attended the SWAMI (Stored Waste Autonomous Mobile Inspector) Phase 2 demonstration at the DOE Fernald Laboratory.

IMSS, ARIES, and SWAMI are DOE barrel-inspection systems using mobile robots. With no duplication or redundancy, ABCD brings value-added and capability-added visual inspection to all three mobile systems; this is because ABCD finds any change, whether understood or interpretable. If the change is large enough or not known to be benign, then it is passed to the interpretation systems in IMSS, ARIES, or SWAMI. If they cannot ascertain that the change is benign, then it will be passed to an operator for decisions. Initially, ABCD will be integrated with IMSS, due to the cost effective circumstance of the recent merger of Lockheed (ABCD project) and Martin Marietta (IMSS project).

WBS Element / Subtask 4.3 Regulatory Compliance Assessment

Subtask 4.3 was effectively accomplished by participating in DOE METC initiatives to consult warehouse operators at DOE laboratories to determine their requirements, both those imposed by regulatory agencies and those of an operational character. This established uniform and realistic inspection and operational criteria for all DOE contractors developing robotic systems for warehouse inspections, including this ABCD project. The ABCD activities in this area are presented in Subtask 4.1 above.

WBS Element / Subtask 4.4 ER&WM Compatibility Review

Since the DOE has taken the lead in focusing the barrel-inspection needs of the DOE laboratories and barrel warehouses, the ABCD project is maintaining ER&WM compatibility by participating and collaborating with existing DOE barrel-inspection requirements determination and existing DOE mobile-platform developments.

In addition, Subtask 4.4 was augmented by attending and actively participating in a DOE METC meeting and by presentation of relevant capabilities at an IEEE meeting.

Dr. Peter Berardo, LMSC, reported the ABCD project at the Environmental Technology Development Through Industry Partnership Meeting at METC, 3-5 October. The report was in the form of a poster session, which provided ample opportunity to verify compatibility of the ABCD project with DOE objectives and approaches.

Dr. Jeremy Wilson, KSI, reported elements of the ABCD project at the IEEE International Conference on Systems, Man, and Cybernetics, Vancouver, BC, Canada, 22-25 October 1995. Dr. Wilson was the primary author and Dr. Berardo was coauthor. The paper was "Automatic Inspection of Hazardous Materials by Mobile Robot". This paper was basically on KSI technology, including examples relevant to DOE barrel inspection. The paper was well received and validated the use of autonomous robots for inspection operations.

WBS Element Task 5.0 Phase 2 Field System Definition

With the opportunity to integrate with the IMSS project, the scope and character of this task changed. Individual subtasks for Task 5 were not pursued in favor of satisfying the Task 5.0 Statement of Work through more general and cost-effective activities.

It was agreed at DOE "bake-off" planning meetings that ABCD would adapt to the field requirements of IMSS, ARIES, and SWAMI. Further, the first robotic platform for ABCD integration would be the IMSS due to the cost-effective and ease of collaboration since Lockheed (ABCD project) and Martin Marietta (IMSS project) merged.

In general, the ABCD project followed DOE METC initiatives and the other DOE projects. ABCD is basing requirements on needs derived from DOE warehouse operators and achievable by existing or planned IMSS, ARIES, and SWAMI capabilities to be demonstrated in the DOE "bake-off", tentatively planned for early 1997.

In addition, in order to achieve compatibility and integration with other DOE barrel-inspection projects, IMSS, ARIES, and SWAMI, the ABCD project visited the Phase 2 demonstrations of each of those projects. Individual platform was observed to assess capabilities and limitations that could impose unique requirements on ABCD beyond DOE operational requirements. This discussed in more detail in Task 4.0 above. The requirements of particular interest to ABCD are summarized in Attachment 5.0

In general, the DOE initiative and direction assured all projects of a cost-effective and uniform set DOE operational requirements. The

WBS Element / Task 6.0 Phase 1 Project Management

The DOE METC CORs and Energetics greatly helped in the management of Phase 1 of the ABCD project. The reporting requirements were extensive but clear.

The ABCD Management Plan, Cost Plan, and Milestone Plan were completed and forwarded to the DOE. The Revised ABCD Management Plan, Milestone Schedule Plan , Quality Assurance Plan, and the Semi-Annual Financial Property Control Report were submitted.

The monthly reports, Status Report, Cost Management Report, Milestone Status Report, and Summary Report, were with one exception, all submitted on time.

Initially Phase 1 proceeded according to plan, meeting Task 1 and Task 2 milestones on schedule and below cost. However, the early, opportunistic, and cost-effective integration of the LMSC ABCD project with the LMA IMSS project caused significant perturbations in the remainder of the schedule. While completion of Phase 1 was delayed, the DOE saved in costs while enhancing the overall barrel-inspection program through early and more direct integration of ABCD with IMSS.

Additionally, the initiative of the DOE METC CORs in establishing DOE operational requirements assured consistent and uniform requirements among all projects and allowed ABCD resources to address the added registration problems presented by the other less precise camera positioning platforms.

It is emphasized that there was no change in the ABCD Phase 1 SOW (Statement of Work) and all SOW tasks were completed. Only subtask emphasis or consolidation was changed by the early integration.

The remainder of the summary for Task 6.0 presents ABCD Phase 1 management highlights.

Kickoff meetings were held internally by LMSC, between LMSC and KSI, and between the DOE and LMSC. An advance purchase order for the KSI Eagle Eye™ system allowed KSI to meet their commitments prior to invoicing LMSC for work performed.

Due to some early procurements for later tasks, there was some early deviation from the cost plan. A new cost plan was completed during January 1995. This plan more accurately allocate material purchases as a function of time and task. Also, due to accounting changes at LMSC, the cost plan was regenerated.

A conference paper , including the results of the Task 1 and Task 2, was submitted by KSI for the IEEE Systems, Man, & Cybernetics conference in Vancouver, October 22-25, 1995. This paper is primarily KSI original work, but one application included the ABCD project.

An abstract, patent release, and author information were submitted to Conference Services, METC, for the Environmental Technology Development Through Industry Partnership conference at METC, 2-3 October 1995. A poster session describing the ABCD project was presented and well received.

A Lockheed Martin Intercompany Work Transfer (IWT) was initiated. This authorized Lockheed Martin Astronautics (LMA), Denver, personnel to work on the ABCD project. In particular, Eric Byler, Project Manager for the Intelligent Mobile Sensor System (IMSS), and Ray Rimey, IMSS image processing, are identified. The role of LMA is discussed in Section 5.0.

A request for a no-cost time-extension for Phase 1 of the ABCD project was initiated. This provided the most cost-effective integration of the ABCD and IMSS projects, which are both DOE / METC and Lockheed Martin barrel-inspection contracts. This is discussed further in Section 5.0.

Due to complications in the images and their analysis, a no-cost time extension of Phase 1 was approved to 20 February 1996.

5.0 Technical Progress Summary

In this section are presented the primary analyses that are the result of the accomplishments above and led to the results presented for each task in the attachments. In other-words, this section provides the technical basis for the ABCD Phase 1 results.

The topics are presented in the same chronological order as the monthly status reports, since one technical result often logically depends on previous technical result. However, each report usually addressed several topics, which are indexed separately here.

(NOTE: TBD: Grammar tense needs to be revised to be consistent.)

Section 5 Technical Topics

5.1 Geometrical Analysis
5.2 Camera Analysis
5.3 Performance Criteria
5.4 Opti-Cal & Eagle Eye™ Enhancements
5.5 Image Processing Subsystem Design
5.6 Application System Integration
5.7 Wide-Angle Lens Selection
5.8 Application System Testing
5.9 Specular Reflection
5.10 Illumination
5.11 Edge Registration
5.12 Radial Distortion
5.13 Camera Stand-Off Distance
5.14 False-Positive Changes and Image Registration
5.15 Improving Image Registration
5.16 Improving Illumination
5.17 Change in Approach
5.18 "Tiling" Image Registration Algorithm
5.19 Image Processing Consultation.
5.20 Integration Plans
5.21 Requested Time Extension
5.22 Image Registration
5.23 Enhancements to System Software
5.24 IMSS Platform Testing
5.25 Tiling for IMSS
5.26 IMSS Experiments
5.27 Preliminary Analysis of Change-Detection Deployment System Data
5.28 Change-Detection ER&WM Field System Compatibility Verification

5.1 Geometrical Analysis

Please see the attachments, "Analysis of Geometry for Drum and Label Viewing" and "Label Size Analysis". An earlier version of these were presented at the project kick-off meeting in Vancouver on October 21, 1994. They show our preliminary results for calculating an appropriate size for the drum labels. The important parameters that we have some control over are: "stand-off distance" (how far away the camera is from the drum), the "face image width" (how many pixels we need across the marker in order to be able to reliably identify it using Eagle Eye; we can do better than the 45 pixels indicated but it is advisable to be conservative at this point), and the number of "faces around drum" (how many marker faces there would be if we repeated the pattern all the way around the drum, which is an important consideration if in the future we need to be able to manage drums that are presented with an arbitrary barrel rotation).

The preliminary conclusion from the analysis was that the total width of the label would be approximately 11.5 inches, consisting of two 2.6 inch square Eagle Eye™ marker patterns separated by 6.3 inches. This is a convenient size for printing on standard legal size paper or sticky label stock, and allows ample room for ancillary text and bar codes. This also allows eight labels to cover the circumference of the barrel to help make the ABCD system independent of barrel orientation. However, twelve labels may give better pose resolution and will also be investigated.

Another important result of the analysis was that the focal length of the wide angle lens required to see the entire drum at close range (approximately 16 inches from the drum) was approximately 3.7 mm, which is close to the limit of what is commercially available. The analysis brought to our attention the importance of having a camera with a larger CCD image area, and was a factor in the choice of a different color camera than earlier proposed.

One fairly obvious but important result is that the camera should probably be mounted on its side so that the longest dimension of the imaging array is aligned with the longest dimension of the drum. As noted earlier, it is also important to use a large area CCD array if possible because this reduces the focal length of the lens needed. As a minimum at present, however, there will still be about 5 pixels per 0.25 inch on the front of the barrel, so that change detection should be reliable in that region.

There were two main equipment issues of relevance: the choice of color CCD camera, and the selection of software to support code development and image analysis. The original camera favored for selection was the Sony DXC-930. However, Hitachi has recently announced a new model, the HV-C20 which, upon examination of the specifications, was better suited to the project and lower cost. It also had a more standard lens mount allowing for use of more standard (and cheaper) lenses. In relation to support software, a review of image processing packages for the Macintosh was conducted, and IPLab Spectrum by Signal Analytics was recommended as the most appropriate choice.

5.2 Camera Analysis

The original analysis of lens focal length was based on a camera with a smaller image array than the one now selected. This early analysis indicated a focal length of 3.7 mm was needed. However, we discovered that such a lens was difficult to obtain. We were also concerned that a very wide angle lens might introduce distortions that are difficult to correct. Using the spreadsheet developed for this project, we studied the relationship between focal length and stand-off distance for the Hitachi color camera. Given an assumed aisle width of 30", a camera body length of 4.5", and allowing for a further 5.5" of clear space behind the camera body leads to a focal length of 4.5 mm (with a camera stand-off distance of 20"). We know that we can obtain this type of lens immediately from a local supplier.

The automatic camera calibration software was put through its paces in a series of batch-mode tests that experimented with its sensitivity to errors in the definition of the calibration target. The result most sensitive to modeling errors turned out to be focal length. It appears that we will be able to measure this to within about plus or minus 1% on calibration targets whose dimensions have been measured by hand. While this is probably adequate, we could use more accurate techniques for measuring the calibration target that would improve the accuracy of the calibration results. We have also started work on updating the Eagle Eye™ software so that the calibration result file produced by the automatic calibration program can be easily read in and used by Eagle Eye.

An analysis was done of the factors influencing Eagle Eye's estimation of the range and pose of a two face marker. This verified what we had already found empirically, that a marker with two non-coplanar faces (with an angle between the faces of around 20-30 degrees) improves both range and pose accuracy, and in particular makes the system fairly insensitive to the orientation of the marker (as long as both faces can be seen). In contrast, pose is difficult to estimate accurately for a single face marker when it is face on to the camera. This is why the proposed drum label will have at least two markers (each about 2.5" square) separated by about 6.5".

Plugging in the values representing the drum inspection situation into the above analysis leads to an estimate of range error of plus or minus 1/20th of an inch, and a pose accuracy of plus or minus 0.3 degrees (along the long axis of the label). The numbers come out of a simplified representation of how Eagle Eye™ solves for the position and orientation of the marker, and so we still need to determine the true accuracy experimentally. However, this analysis was a useful `sanity check' and because it is in a spreadsheet form it is easy to experiment with other scenarios. The results certainly seem to indicate that the drum label geometry will lead to sufficient accuracy to meet the objective of being able to detect changes on the drum as small as 1/4".

We have begun work on setting up the experiments that will measure the positional accuracy for drum inspection, and to evaluate the sensitivity of change detection to changes in illumination. Three drums have been ordered and are due for delivery immediately, and we are in the process of purchasing the lens, lamp, and light meter.

5.3 Performance Criteria

General

WBS Element / Task 1.0, Change-Detection Performance Criteria Determination, was completed. The technical work performed is detailed in the attachment. The results are summarized here.

In addition to determining quantitative performance criteria, work performed in Task 1.0 also produced two software tools for readily adapting the system in the field to changes in system optics or operational requirements.

The first tool is a spread-sheet implementation of a pin-hole camera of the ABCD system optics. This allows rapid change of a parameter value with consistent value determination for other parameters. The most significant parameter in this respect is camera lens focal length. But operational parameters, such as aisle width, barrel dimensions, label dimensions and label placement, and camera positioning resolution, are also included and can be readily changed to study their significance in change detection.

The second tool uses a calibration pattern and image analysis software to allow automatic calibration of camera optics. The tool analyzes captured images of the pattern to find the best consistent set of parameter values for the focal length, the pixel size, the pixel aspect ratio, radial distortion, and image-center. These are critical parameters in relating CCD images to physical objects and in matching images. Previously, this was generally an unsolved problem, with only partial academic solutions. Operationally, this means that camera lenses and/or camera bodies can be changed in the field, the system recalibrated, and new images acquired that can be compared with baseline images. It also means that images obtained with one robot inspector can be compared with images from another robot inspector.

The performance criteria were determined using on-hand software for barrel marker design, rendering, and printing. This quantized dimensions based on screen and printer pixelation. This has resulted in some nonstandard dimensions. In the future, for routine marker production, marker dimensions will be slightly adjusted for ease of production and measurement.

The specific values depended on the rendering and printing methods used, which quantized dimensions based on screen and printer pixelation. When the final lens is procured, marker dimensions will be slightly adjusted for ease of production and measurement.

One issue that will need further investigation in Subtask 2.3, Application System Image Subtraction Test Implēmentation, is lighting. Aspects of lighting are normalization of images from intensity calibration bars on the barrel labels, ambient light subtraction, consideration of the spectrum of controlled lighting, and, possibly, calibration of the lumen response of the camera.

Performance Criteria

The following parameters and values form a consistent set, as determined by the optics model and calibration tools described above.

Camera	
Focal length	4.3 mm
Marker	
Square edge	3.195 in
Separation	5.739 in
Total width	12.129 in
Label positioning on barrel	
Vertical displacement alone	± 1 in
Pan alone	± 30°
Roll alone	± 5°
Pose determination	
Absolute accuracy	
x,y,z	± 0.5 in
tilt, pan, roll	± 2°

when camera is located, relative to label center, at (x,y,z,tilt,pan,roll) = (0,0,0,0,0,0):

x,y	± 4 in
z	18 to 24 in
tilt, pan, roll	± 10°

Repeatability	
x,y	± 0.15 in
z	± 0.2 in
tilt, pan	± 0.8°
roll	± 0.5°
Work volume	
Navigation requirement to see 2 markers on label	
Left-right, in-out	± 6 in
Up-down	± 12 in
Change detection	
Reference spot diameter	0.25 in
Illumination, flat, diffuse, required for repeatability	± 10 %
Geometrical boundary from barrel centerline	± 40°
Change threshold as percentage of contrast range	± 20%
Repeatable change, minimum number of pixels in blob	18 pixels
No change (noise) maximum number of pixels in blob	8 pixels
Analysis rate	
Pose estimate after time of request	0.5 sec
Fine positioning of camera to get final pose estimate	10.0 sec

5.4 Opti-Cal & Eagle Eye™ Enhancements

Further work has been done on the automatic lens & camera calibration software (Opti-Cal) and on KSI's Eagle Eye™ marker tracking software. We completed the porting of these applications to run on the PowerPC processor that is used in the new Power Macintosh line of computers so that we can take full advantage of their improved performance. (It should be emphasized that this porting did not require any structural changes to the programs, merely recompiling them using Symantec's C++ compiler for the PowerPC that has just become available, and fixing a few problems in our code that had not previously shown up on the older Macintosh computers). The speed improvement for Opti-Cal was very dramatic, with a typical calibration operation now taking between 1 and 2 minutes instead of the 15-20 minutes that were previously required. In the case of Eagle Eye™ the speed up is about a factor of two (initial target acquisition takes less than half a second on a 640x480 pixel image and tracking rates are as high as 8 frames a second for tracking a single marker). The reason this speed up is not as large as for Opt-Cal is that Eagle Eye™ is both compute intensive and memory intensive, while Opti-Cal does not exercise memory nearly as much. However it must be stressed that the processing speed we are achieving now is certainly adequate for the drum inspection application.

Two other important improvements to Eagle Eye™ have been made: it is now able to read Opti-Cal's calibration output (previously the information had to be manually entered); and it now supports user definition of the output format for the tracking data, a feature that will simplify integration with the robot controller.

An Opti-Cal calibration target was built and carefully measured (using jig borer which has the ability to make very precise 2-D measurements). The Opti-Cal model file for this calibration target was then generated from these measurements.

5.5 Image Processing Subsystem Design

The image processing subsystem of the ABCD system is based on a number of applications, including KSI's Eagle Eye™ marker tracking software, the Opti-Cal automatic camera calibration software, and Signal Analytic's IPlab™ for image processing. None of these applications is specifically designed for drum inspection, and so there has to be something to integrate these applications and coordinate their activities based on commands sent from the robot controller. In the remainder of this section we report on how we expect this customized integration to be achieved.

Figure 5.1 summarizes the context of the image processing subsystem in the ABCD system. This subsystem has three main roles: determining the identity of a drum; accurately locating the drum markers with respect to the camera (so that the camera can be placed in a consistent position on each visit to a drum); and determining whether any significant change is visible. This subsystem will act on requests either from an operator (at the computer console) or from the computer controlling the robot (which has overall responsibility for managing the automatic inspection task). Its responses are based on the video data it receives from the camera on the robot.

Context Diagram for the Image Processing Subsystem

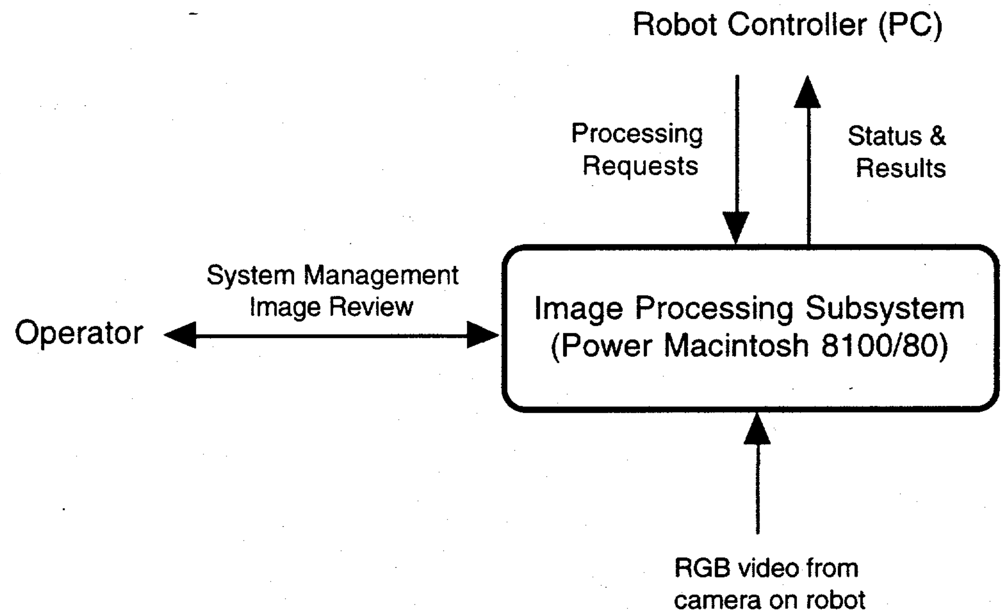

Figure 5.1: The image processing subsystem integrates camera calibration, image collection, and change detection for the ABCD system.

In Figure 5.2 our design for the internal structure of the image processing subsystem is illustrated. The purpose of this diagram is to show the main components of the subsystem and the messages that can be sent between the components to coordinate operation. In this structure, the core functionality is provided by Opti-Cal, Eagle Eye™, and IPlab™. The integration of these applications is to be achieved by the development of a new custom program, the ABCD Image Processing Manager. It will translate requests from the Robot Controller (or operator) into a sequence of lower level requests to the core applications, do any necessary data filtering or reformatting, manage the database of drum images, and report to the operator any drums which may need attention . We believe that this modular approach to the design will make it straightforward for us to adapt and extend the subsystem as requirements for the ABCD system evolve.

The solid arrows in the diagram indicate a message path between two processes in the subsystem. The arrow points to the receiver of the message. Dotted arrows indicate the return of status or results to the sender. Beside each message arrow is a list of the requests that can be made through that message path. The purpose of each of the messages is summarized below.

From the Robot Controller to the ABCD Image Processing Manager:

Calibrate Optics: the camera has been positioned in front of an Opti-Cal calibration target and a recalibration of the lens/camera/frame-grabber intrinsic parameters (pixel aspect ratio, radial distortion, lens focal length etc.) should now be performed;

Calibrate Intensity Response: the camera has been positioned in front of an intensity calibration target and a recalibration of the camera/frame-grabber illumination response characteristics should now be performed;

Report Label No. & Pose: report on the id. and pose (position and orientation of the label relative to the camera) for any drum labels that can currently be seen by the robot's camera;

Save Baseline Image: save the image last captured by Eagle Eye™ (in response to a Report Label No. & Pose request) in the image database along with the drum id., label pose, calibration settings, date, time, and any other relevant information;

Report Desired Position: for the drum currently being viewed, report the pose that needs to be achieved in order for the camera to be in the same position that it was in when the baseline image for this drum was captured;

Perform Change Detection: save the image last captured by Eagle Eye™ (in response to a Report Label No. & Pose request) and compare it to the baseline image for the drum currently being viewed.

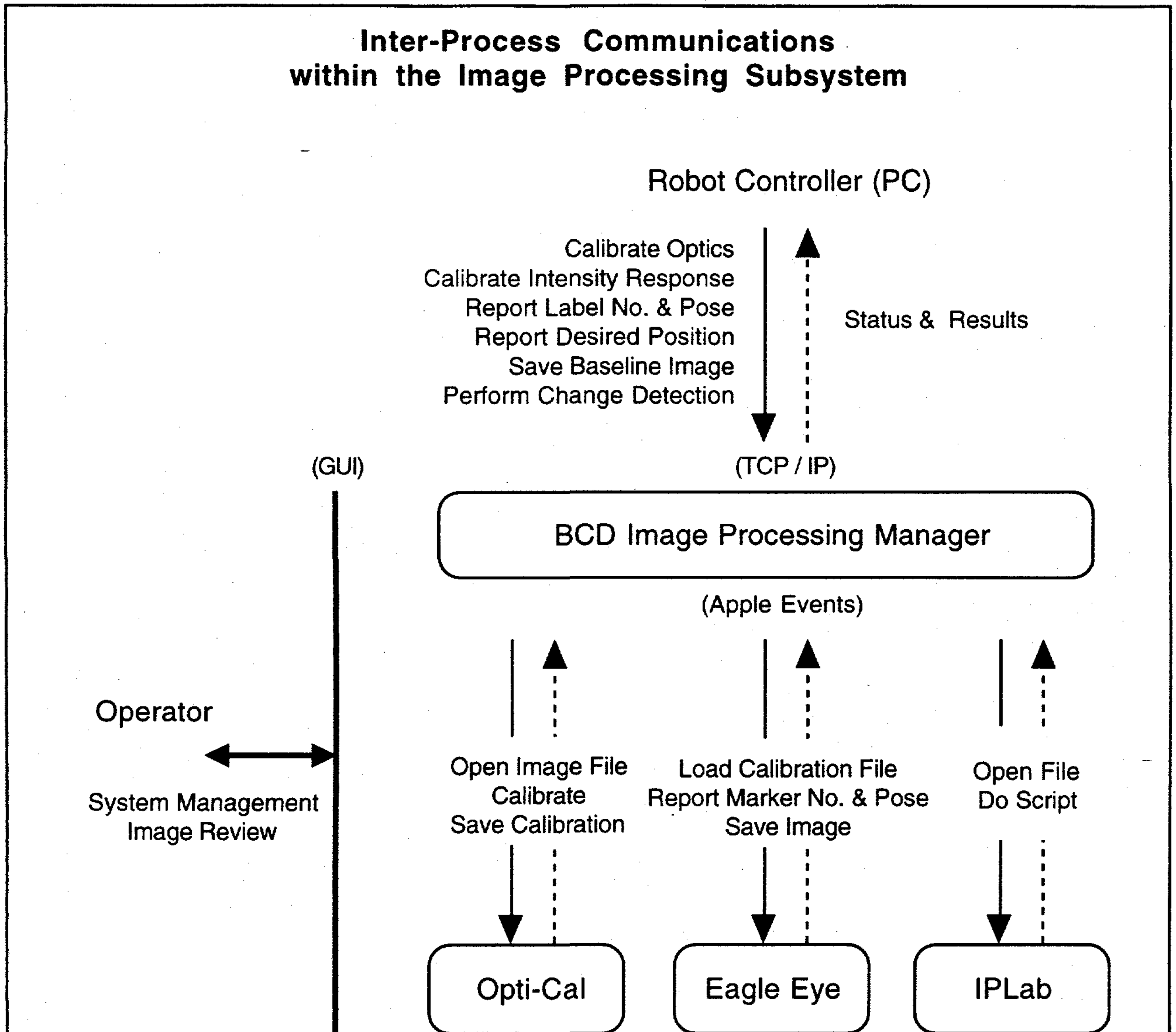

Figure 5.2: The ABCD Image Processing Manager coordinates the activities of the Image Processing Subsystem in response to operator commands or commands from the Robot Controller.

From the ABCD Image Processing Manager to Opti-Cal:

Open Image File: open the specified image file;

Calibrate: run the automatic calibration procedure on the current image and report success/failure;

Save Calibration: save the result of a successful calibration.

From the ABCD Image Processing Manager to Eagle Eye™:

Load Calibration File: load the specified Opti-Cal lens/camera/framegrabber calibration file;

Report Marker No. and Pose: report on the id. and pose (position and orientation of the label relative to the camera) for any Eagle Eye™ markers that can currently be seen by the robot's camera;

Save Image: save the image last captured (in response to a Report Marker No. & Pose request) to the specified file.

From the ABCD Image Processing Manager to IPlab™:

Open File: open the specified file (image or script);

Do Script: run the specified script (e.g. change detection or intensity calibration).

Operator interaction:

System Management: initial set-up and routine maintenance of the Image Processing subsystem;

Image Review: the Operator is presented with an activity log highlighting any drums that the operator may need to check for deterioration;

Different message protocols apply to the various message paths. We anticipate that messages from the Robot Controller will be sent using the TCP/IP protocol over an Ethernet link between the Robot Controller and the Image Processing computer. Messages between applications running on the Macintosh will use the standard Mac OS messaging protocol known as Apple Events (used for communicating between applications that are running on the same Macintosh computer or between applications that are running on two different Macintosh computers connected to a network). The operator will interact with the components of the image processing subsystem through the graphical user interface (GUI) associated with each of these tools. In Task 2 the Image Processing Manager will have a fairly basic user interface that just allows us to simulate requests so that we can test this component prior to integration with the robot controller. The initial implementation of the Image Review function will also be fairly simple in Task 2 and will be expanded in Task 3. Integration of the calibration functions will not be implemented in Task 2. The operator will perform any necessary calibrations using Opti-Cal and IPlab™. The implementation of fully automatic calibration (in which the robot automatically visits a calibration target) will be left to some later stage in the ABCD development since it is not essential for demonstrating the ABCD operational concept.

The most complicated task for the Image Processing Manager to coordinate is the change detection task. Figure 5.3 illustrates how the data flows between the processes involved in the change detection task, and also indicates the sequence of steps required to perform the task (the arrows in this diagram indicate the flow of data; it does not show the messages between the processes). There are eight main steps:

1. Report Label No. and Pose: the Image Processing Manager requests the label id. and pose for the drum currently being viewed, and confirms that the camera is in the same position that it was in when the baseline image for this drum was captured (if not, an error is signaled);
2. Save Image: Eagle Eye™ is asked to save the image captured in step 1 to a file that IPlab™ can read.
3. Retrieve baseline image from database: the Image Processing Manager retrieves the baseline image of the drum from the image database in a form that IPlab™ can read.
4. Run change detection script: IPlab™ is instructed to execute the sequence of image processing operations specified in the change detection script
5. Output results: IPlab™ saves the results of the change detection processing in a text file.
6. Examine results: the Image Processing Manager examines the results of the change detection processing (it may access the image database to determine if any minor changes that are visible now were also present in other recent inspections of this drum, in which case the change may be flagged as worthy of further investigation by the operator).
7. Save New Image to Database: the new image of the drum will be saved in the image database so that the operator can compare the baseline and new image of the drum if it is flagged as changed (older images may be purged or archived to tertiary storage such as magnetic tape).
8. Report completion: the success or failure of the change detection task is reported back to the Robot Controller or Operator.

In Phase 1 only nine drums will be used for demonstrating the system, so the image database will be implemented as a simple flat file database (i.e. there is no need at this stage for something like a relational database, which would require a greater level of effort to integrate and manage).

We have done some preliminary implementation work on the ABCD Image Processing Manager to test the use of Apple Events, and to test the use of multi-threaded execution (in which several threads of execution operate simultaneously within one application so that, for example, task sequencing for change detection can proceed while at the same time remaining responsive to any new requests).

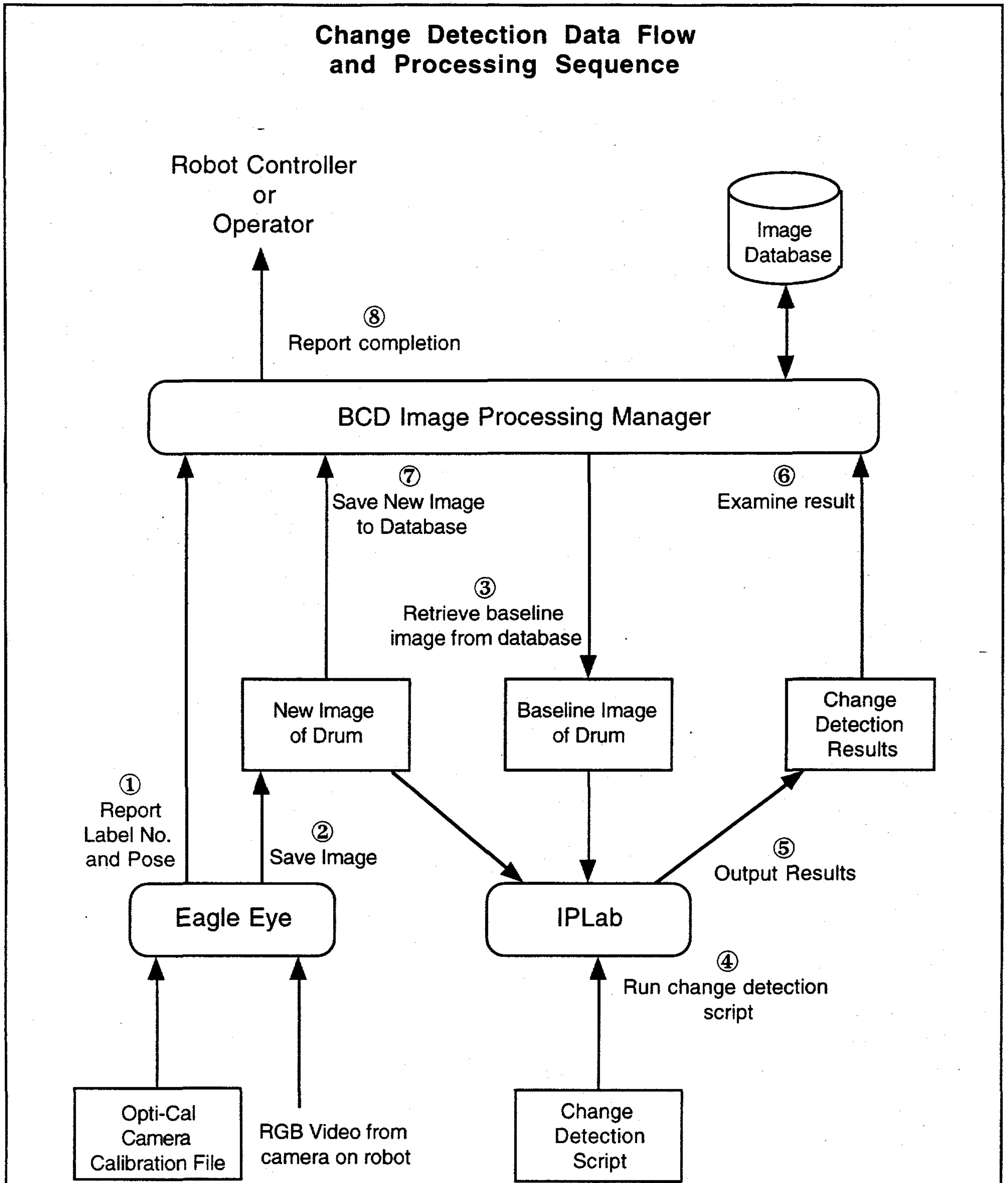

Figure 5.3: The ABCD Image Processing Manager controls each step in the change detection process, and maintains the drum image database.

5.6 Application System Integration

The IPM is a suite of four components (separate programs) running on a Power Macintosh: Eagle Eye™ for determining the position and orientation of the drum labels with respect to the camera; Opti-CAL for automatic camera calibration; Signal Analytic's IPLab for image processing; and the Image Processing Manager (IPM) which provides overall supervision of the other programs and manages communications with the rest of the ABCD system. The architecture of this set of components was discussed above.

The Image Processing Manager (IPM) was implemented, integrated with Lockheed's R2X robot control computers, and tested. Eagle Eye™ was also extended to enable it be controlled via "Apple Events" (an interprocess communication mechanism supported by the Mac OS). The protocol for communications between the IPM and the program controlling the R2X robot arm was defined, and command sequences were run to test two important ABCD tasks: establishing a baseline image for a drum, and revisiting a drum to perform change detection. A calibration problem (described next) prevented these tests from being as realistic as we would have liked, but it will be straight forward to re-run the tests again once the calibration procedure is completed.
One problem encountered during the integration testing was the need to accurately calibrate the offset between the "tool plate" (the robot wrist, whose position can be accurately commanded by the R2X control computer) and the camera's focal plane (which is the point of reference for Eagle Eye's measurements. A procedure was developed by Bill Dickson (Lockheed) to move the arm through a sequence of positions while acquiring Eagle Eye's measurement of the pose of the drum label for each position. While the calibration problem was not completely solved during the integration task, the calibration procedure itself proved to be a good test of the communications between the computers, and helped us to identify and solve a number of minor problems.

5.7 Wide-Angle Lens Selection

As noted earlier, we encountered a mechanical incompatibility between the 4.2mm Cosmicar lens (used during the phase 1A) and the Hitachi 3-CCD camera. This new camera has more stringent requirements for the type of C-mount lens that can be used with it. Unfortunately there was no information in the camera specifications to alert us to this fact, so the problem was not encountered until we received the camera. The likely change in minimum aisle width from 30" to 36" also presents an opportunity to select a lens with a narrower field of view (and hence lower radial distortion). Further, our recommendation at the end of phase 1A was that a higher quality lens should be considered to achieve the best focus through out the image and lower radial distortion. We investigated options for wide angle lenses that would work with the new camera, and found that there was quite a limited selection. Our recommendation at this point is that we purchase a 5.7mm Century Precision lens. We tested this lens in Phase 1A and found it to have much lower radial distortion than cheaper lenses of comparable focal length (these cheaper lenses also would not work on the new camera).

5.8 Application System Testing

A draft test plan for Subtask 2, Application System Verification Testing, was written. The tests in this plan will provide quantitative estimates of change-detection reliability. For example, the False-Positive error rate, i.e., the expected uncertainty between the predicted False-Positive rate and the measured False-Positive rate, will be determined during the tests. (The absolute False-Positive and False-Negative rates are determined by user-controlled criteria, such as blob size and contrast thresholds.)

The test plan is being delayed until various lighting issues are resolved. Lighting criteria and performance tests will then also be included in the test plan.

The general performance of camera repositioning (pose replication) with a robotic manipulator was verified. The CCD camera on the end of the R2X manipulator was repeatedly repositioned so that it was centered on the barrel label and the barrel pose reestablished. The positioning accuracy was about a factor of two better than the performance criteria established in Task 1. A complete set of positioning tests will be conducted when the lighting issues are resolved.

During integration and preliminary testing it was determined that camera calibration and absolute change detection are very sensitive to lighting conditions. Although ambient-light background subtraction is being performed, there is a very small range of conditions between camera saturation due to specular reflections and loss of pose due to too little light on the barrel label. Generally, these issues will be resolved by better light control, minor algorithm changes, and tuning of image-processing parameters.

5.9 Specular Reflection

The image of an illuminated object is primarily a function of its diffuse reflection property. Diffuse reflection scatters the incident light equally in all directions. The amount and specific wavelength of the reflected light is a direct property of the material and geometry of the object that is being observed. A defect on the drum can be viewed as a change in the underlying material's property. This leads to different diffuse reflection characteristics and thus can be detected by examining changes between baseline and inspection images.

However, when the surface has a shiny coat as in the case of latex paint, the drum exhibits additional specular reflection. Contrary to diffuse reflection, specular reflection is highly directional and far more intense. One will observe specular reflection on only localized areas where the path to the light source and viewer are almost perfectly aligned on either side of the surface normal. The intensity of this reflection peaks and falls off rapidly as one deviates from such a localized area. Yet within these locations, the diffuse reflection (i.e.. actual image of the drum) is overwhelmed by the specular reflection. What one is then observing is not the drum material itself but rather a reflection of the incident light. The locations of these specular reflection spots are very sensitive to the relative location of the light source, the camera, and the drum itself and, of course, the instantaneous surface normal of the drum. If there is a slight shift in the position of the camera and lights relative to the drum, the specular highlight moves on the drum. Since the intensity distribution of the specular highlights is a nonuniform sharp peak, even a small shift can lead to a change in observed intensity over most of the area of the specular reflection, as shown in the following Figure 5.4. The resulting difference will be registered as false-positive change unless properly handled.

Currently, we are investigating a number of different techniques on correctly identifying specular reflection based on image contents :

- By variation in light position
- By variation in illumination level
- By detection of area with sharp intensity gradient

In order to better facilitate progress along parallel fronts within the project, a fixed geometric mask (manually produced) is currently being used to filter out potential specular highlights. This allows us to proceed with system testing on change detection sensitivity. Eventually, it will be refined with an automatic technique based on image contents.

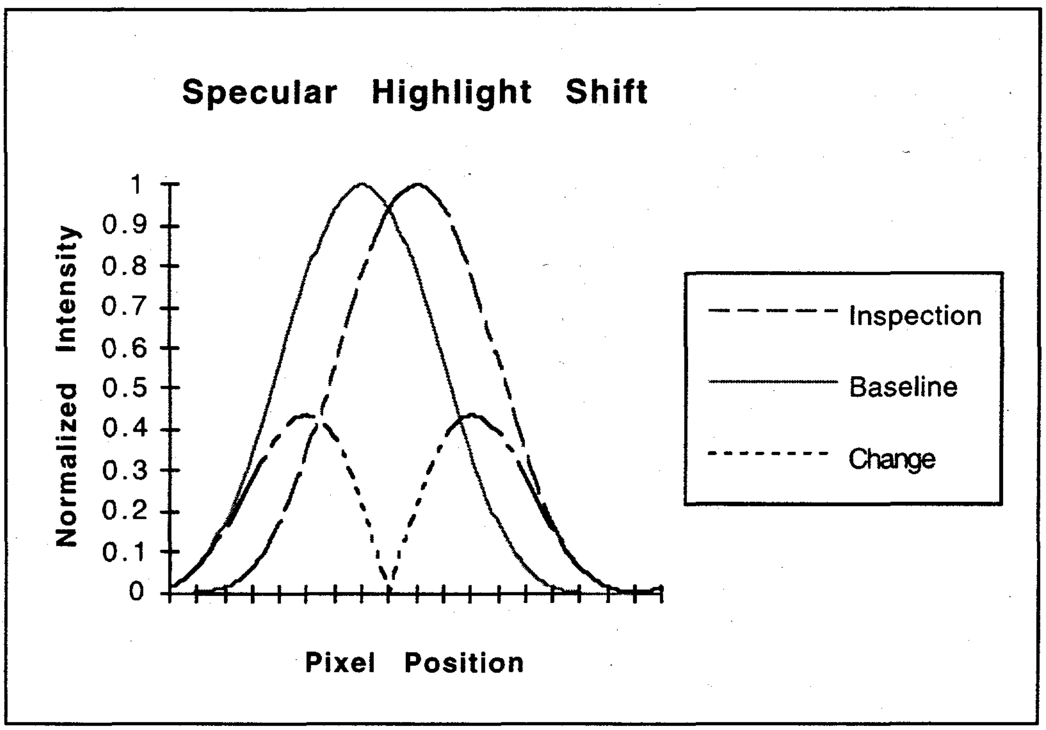

Figure 5.4. Detected changes may be due to spatial shifts of specular reflections.

5.10 Illumination

The capability of the change detection module to correctly identify a defect clearly depends on the observable contrast between the baseline and inspection images. The observable contrast, however, is a function of not only the actual physical alteration of the underlying material, but also the level of illumination. Therefore, it has always been a primary goal of this project to achieve better, and more even, illumination over the observable drum surface.

It is recalled that our procedure already is compensating for ambient light by taking the difference between ambient-plus-controlled-source and ambient-only. And to account for variations in total illumination from baseline to inspection, the barrel label includes a camera-intensity calibration pattern. This allows for operational variations when lights are changed. In this discussion, we assume that ambient light has been subtracted and that intensity normalization has been done.

In general, an object illuminated by a point light source, whose rays emanate uniformly in all directions from a single point, will receive incident illumination of varying intensity at different points on its surface, depending on the direction of and distance to the light source. The drop in illumination intensity is particularly pronounced with the cylindrical drum surface where there is a rapid change in instantaneous surface normal. Consider the case of a single point light source situated at a standoff distance of 24" from a 12" radius drum, as shown in Figure 5.5.

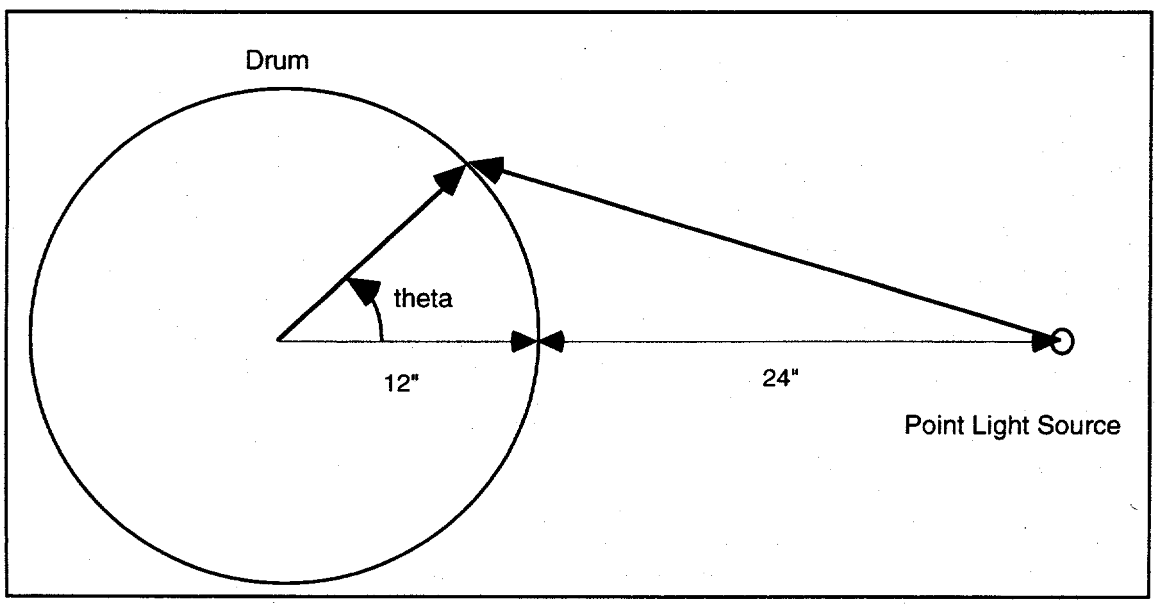

Figure 5.5. The amount of reflected light reaching a camera is dependent on the geometry of the illuminated object.

The incident illumination drops very rapidly as one deviates from the center with an angle of theta. The result is graphically illustrated in Figure 5.6 as the dashed line. Note that at an angle of 30, the illumination is already down to 60% of the maximum. It is clear that additional light sources must be placed to compensate for the drop due to any single light source. Note also that this simple model only defines the *incident* illumination. The observed image is due to the *reflected* illumination, which is a function of the incident illumination, the material property, as well inverse square law attenuation due to the varying distance to the camera. To balance out all these factors, we have two light sources spaced radially at an angle of 43 degree from the drum center. They are all at a standoff distance of 24" as before, the total reflected light (based on a simple point light source model) as one varies theta is shown below as the solid line.

Note that this arrangement distributes the light much better over the cylindrical surface of the drum and provides a theoretical maximum drop of only 9% over the entire 45 degree range. In reality, the drop was more because the track light is not a perfect point light source as assumed. Nonetheless, it does provide a good starting point for our lighting setup, and the resulting image is much better illuminated, especially on the side. However, in order to ensure adequate lighting in the center, it was found necessary to add an extra light in the center to compensate for the drop. The relative intensity of this center track can be tuned experimentally to achieve better and even illumination over a wide area. To provide more even illumination along the drum's vertical axis, two sets of three lights were deployed above and below the camera.

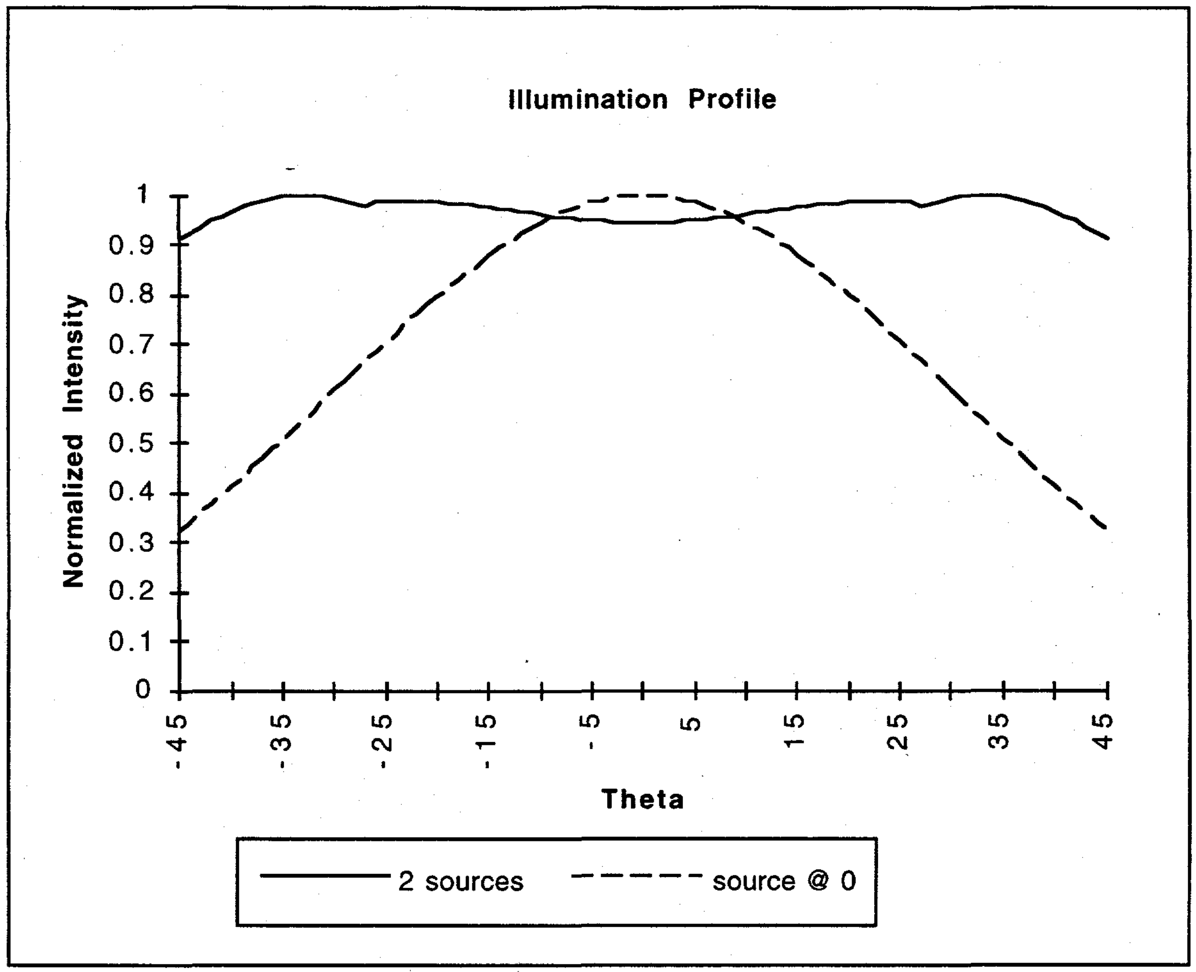

Figure 5.6. Relative incident intensity for one and two sources of illumination, which shows the importance of multiple light sources.

Finally, it is noted that our performance criteria are rather strict. In particular, we are striving for detecting a change in a 1/4" diameter spot, which is only three pixels at barrel center. And a change is defined to be only ±20% in absolute camera response relative to the baseline image. Thus, even 10% changes in illumination are of concern.

5.11 Edge Registration

The registration process currently uses a cross-correlation method to compute the number of pixels to shift in X and Y in order to bring the baseline and inspection images into alignment. Currently this is done only using known features of the barrel label. The resolution of registration is limited by pixel resolution. It is highly likely that the actual amount of physical movement, due to variations in pose alignment, does not fall exactly on a pixel resolution unit. This will not present any problem to relatively constant intensity patches. The only location where we might observe misalignment is on the edge where there is an abrupt change in intensity. If this were an ideal edge where change in intensity occurs instantaneously, then the width of the detectable contrast is simply the extent of the misalignment, which will be less than a pixel. However, in a real image, an edge will typically be slightly defocused, so that rather than an instantaneous change in intensity, the change happens over a finite width in a more gradual fashion. As a result, any misalignment will lead to a change area that is a function of both the misalignment and the edge, as indicated in Figure 5.7.

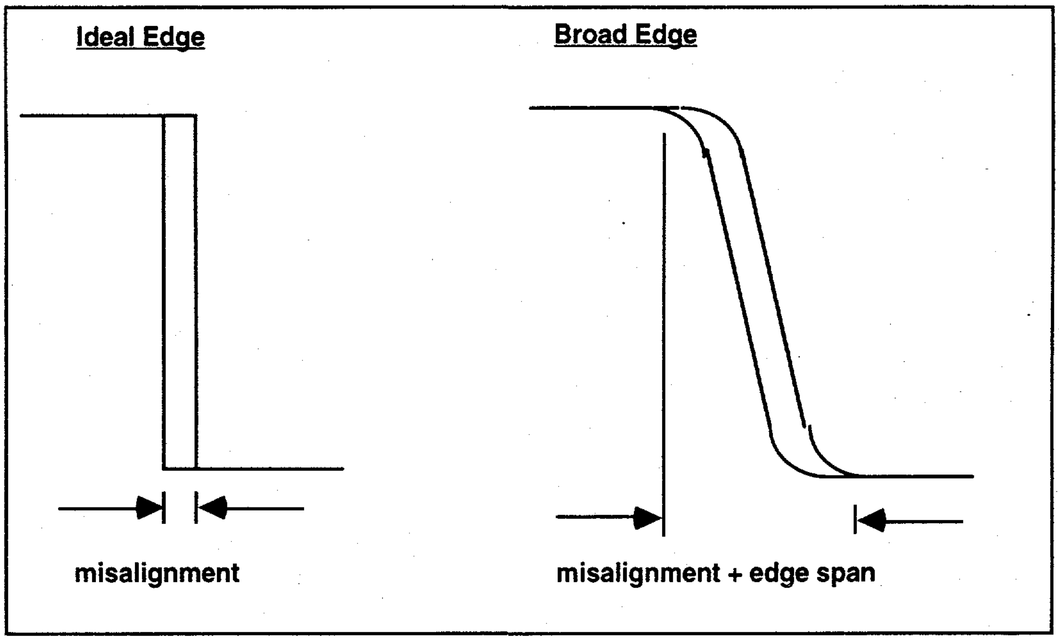

Figure 5.7. Detecting edges of changes depends on both pixel resolution limits and actual illumination fall-off.

Whether this will be registered as a valid change depends on two factors :

- the width of the area over which the change occur;
- the intensity level of the resulting difference.

In our current specification, we reject changes smaller than 3x3 pixels or with a contrast of less than 20%. In order to avoid detecting false-positive changes due to edge misalignment we will need to register the images *to within 1/4 of a pixel.* This requirement for subpixel registration was not appreciated earlier in the project and will require a more sophisticated approach to image registration than we are using at present. Non-translation types of misregistration (radial distortion, image rotation, image scaling, and drum tilt) also indicate that this registration needs to be performed differently in different parts of the image (an approach to dealing with this is described in the next subsection). An analysis and report of these effects is being prepared.

5.12 Radial Distortion

The effect of a lens with positive radial distortion, such as the one currently used in this project, is that as one moves away from the image center, the scene is more compressed so that a single pixel will cover a larger area on the periphery than it will in the center. Since registration is a linear process and the label pattern in the image center is being used as the region of interest for registration, the pixel amount to be shifted over the entire image will be dictated by the center. The varying resolution of the image leads to misalignment on the periphery even though the center might be perfectly aligned. This, compounded with the problem of registering defocused edges discussed earlier, can result in large observable contrast between baseline and inspection images. This phenomenon was not observed previously because the illumination in earlier study was inadequate on the periphery to bring out such observable contrast. Now that we have achieved much better illumination coverage over the drum surface, this radial distortion issue must be properly dealt with. The following lists a number of potential solutions to the problem:

- Use a higher quality lens with little distortion. This will be the ideal solution providing a lens of the proper focal length could be located to handle the aisle width.
- Correcting for the distortion based on the radial distortion model derived through OptiCAL. In this case, the distorted image would be remapped to an undistorted one by reversing the distortion model pixel by pixel. While computing the mapping function for each pixel is an expensive function, it will only need to be done once and stored in a look-up table for correcting future images taken through the same camera and lens setup.
- Allow non-linear shift by multiple region registration. The idea is to divide the image into a number of overlapping tiles and each tile will be registered separately so that variable amount of shifting in the center and periphery can be accomplished. Another potential benefit of this technique is that if the tiles are small enough, it will be able to accommodate small rotational changes. However, the feasibility of this technique depends on how well we can identify specular highlights so that they can be ignored in the subsequent registration process.
- Increase the arm positioning accuracy so that no linear shifting is needed. This is the approach taken currently so that we can proceed with the change detection criteria testing. While it may appear to place overly stringent requirement on the robot arm positioning mechanism, it is simply the lower bound on how accurate positioning must be achieved, and with future enhancements to handle radial distortion, the positioning requirement can be relaxed.

5.13 Camera Stand-Off Distance

The stand-off distance for the color camera (measured from the C-mount) has proven to be greater than anticipated due to an error in the camera data sheet in regard to the CCD imaging area. The imaging area is smaller than expected, and so the camera's field of view is correspondingly reduced.

Reducing the stand-off distance requires choosing one (or a combination) of the follow options:

a) return the Hitachi camera and obtain a camera with a larger format CCD;

b) obtain a lens with a shorter focal length to increase the field of view (the next common size down from 5.7 mm is 3.5 mm which reduces the stand-off distance by approx. 10", but is extremely wide angle and is likely to have an unacceptably high degree of distortion);

c) view the drum from an angle, rather than from directly in front (as shown in Figure 5.8 for the case of a 28.4" stand-off; a margin of 6" is achieved for a viewing angle of 23°, and margin of 9" is achieved for a viewing angle of 44°; the Denver robot uses two cameras per drum in a similar fashion, although the angle may be less);

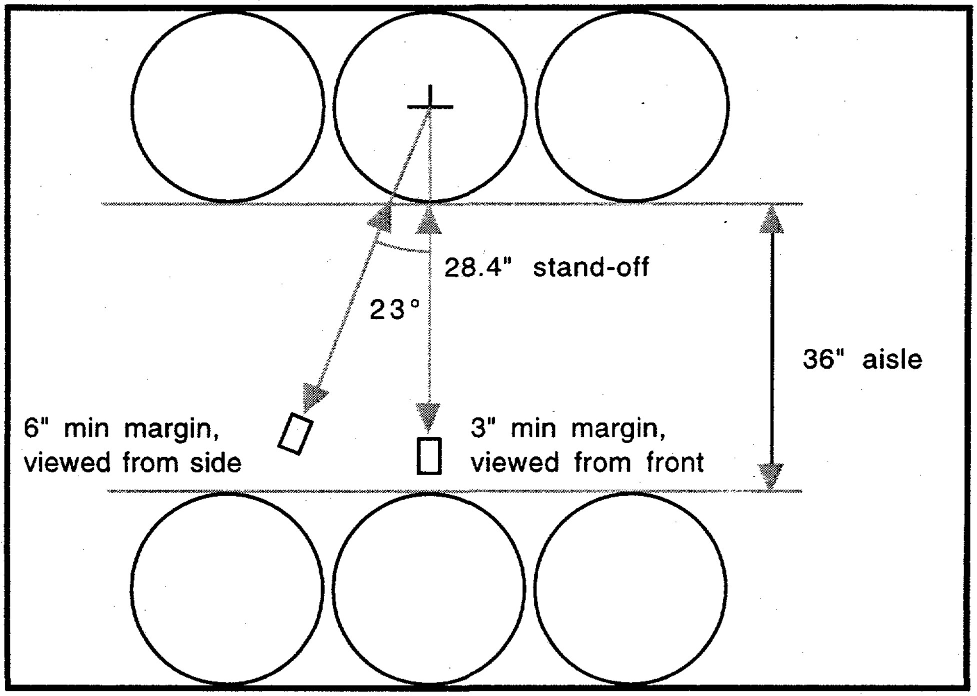

Figure 5.8. Multiple side views can increase the effective space behind a camera.

d) take two images of the drum, either from two oblique viewpoints as on the Denver robot, or a top 2/3 image and bottom 2/3 image, giving a margin behind the camera of approx. 11" (this has the additional benefits of allowing the Eagle Eye™ label to be reduced to about 2/3 of its current width, and improving the resolution of features on the drum, however it increases processing time and camera positioning time);

e) reduce the tolerance to label misplacement (currently specified as 1") so that the viewing margin above and below the drum can be reduced (label positioning could be made quite consistent through the design of a label applicator that used the drum ribs to align the label, and would reduce the stand-off distance by approx. 1" which is a fairly small gain).

5.14 False-Positive Changes and Image Registration

Currently the baseline and change images are registered by vertical and horizontal shifts of integral pixel offsets to maximize the image correlation in the central region of the image. Typically these offsets are only one pixel in size, consistent with positioning criteria. However, when there are high-gradient areas in the images, a small offset can lead to large changes in absolute intensity. This is particularly true at the edges of the image and at edges of features in the images.

The reason that edges become misregistered between a baseline image and a new image is that there are small but real limits on the repeatability of the camera positioning. Errors in camera position manifest themselves in a variety of ways:

- rotation - camera roll axis;
- translation - camera x, y, and yaw axes;
- scaling - camera z (global scaling effect),
  - pitch (scaling-like local distortion),
  - lens radial distortion (scaling-like local distortion).

Several registration solutions are being considered to reduce the false-positive rates due to positioning differences registration. These are tiling, mapping, and recasting.

Tiling: This solution to improved registration is to break up the image into a set of tiles whose size is small enough that the combined effects of the rotation and scaling type distortions is less than the maximum allowable misregistration (a technique which is used by some motion picture compression techniques such as MPEG). Then translation-based registration of each individual tile should result in better matching between the baseline and new image. Our analysis also shows that the registration needs to be to within about 1/4 of a pixel.

In order to match image tiles that have been scaled and rotated, a tile size is needed that ensures the local misregistration that will remain, after the translation component has been removed, is smaller than the allowable misregistration. Analysis shows that a tile size of 32 x 32 pixels is likely to be small enough.

To date, we have implemented a subpixel registration algorithm, including the ability to incorporate the specular mask so that the specular reflections do not bias the registration. We have also simulated the tiling idea by extracting small pieces of imagery from a pair of drum images and running the registration algorithm on these individual pieces. Figure 5.9 summarizes the result of one test in which the maximum intensity of detected 'changes' (known false positives) is compared for two different approaches: the current approach to change detection in which the entire image is registered based on a central portion of the image; and the tiling approach, in which tiles are locally registered (the tile size for the test was 48 x 48 pixels).

Notice that the greatest relative improvement is in the periphery (top and bottom of the drum) which is what we would expect to see, since the peripheral regions are the furthest from the region used to register the image (in the original approach). The values in the table are also shown for the image without any morphological filtering applied. Filtering further reduces insignificant changes, and in the case of these test tiles completely eliminated the false positives.

Approximate Location of Tile with respect to the Drum	**Current Approach:** Maximum Change for single registration (gray levels)	**Tiling Approach:** Maximum Change for local registration of tile (gray levels)
Top of drum	36.0	9.5
Middle of drum and to one side	32.9	22.4
Bottom of drum	96.7	15.8

Figure 5.9. Tiling, which extends central registration to image edges, can significantly reduce the false-positive rate.

We estimate that about 7 days of additional effort are required to complete the implementation and testing of this tiling technique. Although we have not had the opportunity for thorough testing, we believe that this technique will enable us to meet the original pose repeatability specification defined in phase 1A. It may be possible to cope with even larger positioning errors, but we have not performed any tests to determine this as yet.

<u>Mapping:</u> The Eagle Eye™ system provides the pose estimate of a barrel relative to the camera. In addition, the camera parameter values are known. Thus it is possible to remap pixels of one image onto pixels of either a second or a standard image. This is the most direct method. In fact this method must be used when the centers of images are not already closely correlated. For example, ± 2 cm difference is would be larger than the tile edges of the previous method.

However, this more general and direct method may require more processing time. Ancillary issues related to mapping quantized pixels involves averaging and interpolation for non-integral pixel alignment between two images.

Mapping will be considered further.

<u>Recasting:</u> A third, but largely unexplored, possibility is to transform each image from pixel intensities to pixel gradients and to register gradients rather than coordinates. This is analogous to feature registration, but is done on a pixel level to first find the features. This method may also improve change detection regardless of the magnitude of values being compared.

Recasting will be considered further.

5.15 Improving Image Registration

The recent systematic testing of the Application System provided us with a large number of image samples from which to test ways to reduce the false positive rate. Bill Dickson of Lockheed R&DD selected a set of six image pairs (baseline image and change image) that showed a high level of false positives.

We have implemented a prototype of the image tiling approach described above (and in more detail in a separate memo "Proposal for Smarter Change Detection" dated April 20, 1995) so that the idea could be tested on these new images. A summary of the results is presented below in Figure 5.10. The results show the number and total area of false positives that were classified as significant changes. A fairly conservative (i.e. sensitive) threshold of 20 gray levels was used for this test.

	Old Method (simple registration)		**New Method** (tiling & subpixel registration)	
Image Set	**# False Changes**	**Total Change Area**	**# False Changes**	**Total Change Area**
1 (A916)	9	504	0	0
2 (A913)	7	1196	0	0
3 (A912)	3	67	0	0
4 (A911)	4	202	0	0
5 (A711)	46	3266	7	312
6 (A5158)	42	3585	12	1764
Totals	111	8820	19	2076

Figure 5.10. Comparison of False Positive Rate for Old and New Image Registration Methods.

In the first four image sets that were tested the significant false positives were completely eliminated (in image set 3, two small moderate changes remained, but were close to the threshold change intensity). In the remaining two image sets (5 & 6) the number and area of false positives was significantly reduced but not eliminated. The majority of these remaining false positives were found to be due to specular highlights and image saturation (around the label). While these problems need to be dealt with, they are not the result of misregistration. In the case of image set number 5 there were two significant false positives detected (with a total area of 112 pixels) which were not due to specular reflections or saturation, and appear to be a misregistration problem. This may be due to a bug in our prototype implementation, or may highlight some limitation of the approach.

Overall we are very pleased with these results. Clearly this is a limited test, but it does show that the technique shows promise, and is worthy of further investigation and testing.

5.16 Improving Illumination

We investigated an alternative illumination set up that may prove useful as a replacement to the current illumination set up on R2X that is bulky and has problems with achieving even illumination.

A metal foil was bent into a roughly parabolic shape based on a ray tracing analysis. The objective of the analysis was to choose a reflector design that would provide an even illumination of the drum from the camera's perspective. It turns out that the periphery of the drum needs to have a lot more light incident on the drum surface than does the center of the drum in order to achieve a reasonably even illumination from the camera's view point. This is because of the drum curvature and an intensity fall-off effect known as the cosine law that is particularly pronounced for wide angle lenses. At the focus of the reflector was placed a 4 inch linear 500W quartz halogen light source. A picture of the prototype lighting system is shown in Figure 5.11.

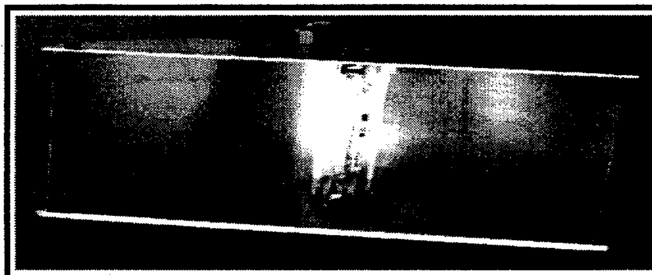

Figure 5.11. A shaped prototype reflector with one light source achieves more uniform lighting of a barrel than multiple light sources.

The light and reflector were placed at a distance of approximately 30 inches from a drum and images of the drum were captured so that the illumination profile could be determined. A representative profile is shown in Figure 5.12. This intensity profile is for the lower section of a drum that was painted white.

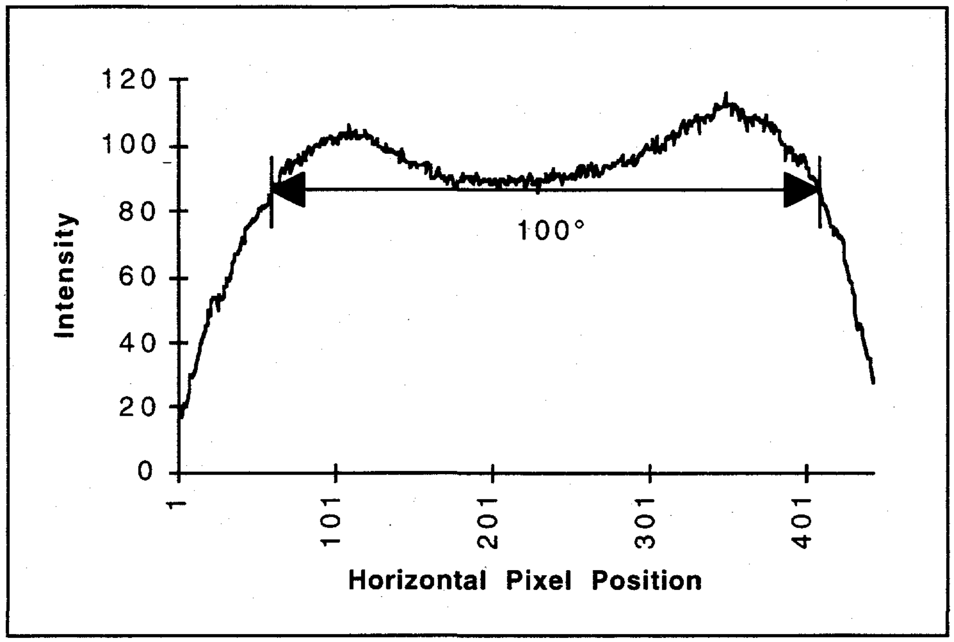

Figure 5.12: Example of Intensity Profile for Experimental Illumination Setup

This lighting set-up achieves reasonably even illumination (approx. ±10%) over a range of approx. 100° of the drum's surface (where the angle is measured from the drum center). We believe this reflector shape could be refined somewhat to improve on this. One potential disadvantage of the design that was noted was that it created a large specular reflection in the center region of the drum, an image of the larger reflector size. If there were labels in this region then it would not be such a problem. Another area where the light source needs improvement is in the selection of light element. The 500W bulb used in the test is too power hungry and hot for a mobile robot. A strobe lamp would probably be a good choice to replace this.

5.17 Change in Approach

The following is adapted and updated from the Draft New Approach, May 1995 Status Report, Section 6, Assessment of Current Status. The Introduction, Definitions, and Premises are unchanged. The Approach was updated based on current assessment of objectives and capabilities.

Introduction (unchanged from May 1995):

The opportunity to integrate the ABCD and IMSS projects changes the scope of work for ABCD in the areas of mobile platform demonstrations in the laboratory (Task 3) and mobile platform design for the field (Task 5). Additionally, the active determination of DOE site operational requirements by the DOE itself reduces the scope of ABCD requirements to determine those requirements (Task 4). Thus, there are both significant new opportunities and emphases. But these in turn will require some changes in the formal Statement Of Work (SOW). The end objectives of this project does not change, but the emphasis does change from precise mechanical control to precise image control.

Definitions (unchanged from May 1995):

ABCD	Automated Baseline Change Detection, Lockheed Missiles & Space Company, Inc., (LMSC), Palo Alto, CA
IMSS	Intelligent Mobile Sensor System, Lockheed Martin Astronautics (LMA), Denver, CO
AIRES A	Robotic Inspection Experimental System, University of Southern Carolina
SWAMI	Stored Waste Autonomous Mobile Inspector, Savannah River Technology Center

Premises (unchanged from May 1995):

1. Integration of ABCD with IMSS is essential.
2. Integration of ABCD with SWAMI and AIRES is desirable and expected.
3. IMSS, SWAMI, and AIRES platforms do not have pixel-level positioning.
4. IMSS, SWAMI, and AIRES platforms do not have similar lighting systems.
5. Enhanced image processing, beyond that used to date, is required to reduce false-positive changes for expected and planned pose and positioning capabilities.
6. The four IMSS images obtained during inspection have fields-of-view fixed with respect to one another, so that if the pose of one image is known relative to one camera, then all poses are known with the same resolution relative to that camera.

Approach (changed from May 1995):

1. For ABCD Phase 1 continue to use Eagle Eye™ system for pose determination.
2. KSI provides LMA with Eagle Eye™ labels
3. Determine LMA characteristics for scanning labels, i.e., lens focal length, camera type, camera calibration data.
4. LMA determines IMSS nominal position repeatability as presently operated.
5. KSI to complete the tiling algorithm for image registration.
6. LMSC / KSI use R2X and ABCD hardware and software to refine image processing methods to register two images offset with spatial displacements consistent with the results of 4. above.
7. LMA sends to LMSC sets of inspection images for registration validation.

8. LMSC / KSI continue to use R2X and ABCD hardware and software
to reduce false-positive rate.
9. Mount the top-mast element of the IMSS system on R2X
to collect and register IMSS-like images with
IMSS-like positioning precision.
10. Plan in ABCD Phase 2 to use natural barrel features for pose determination,
and possibly gradient-methods for image registration.
The Eagle Eye™ system could still be used for pose determination
from natural features and possibly for barrel identification,
smaller labels, if any, are required.

This new approach will require changes in the Statement of Work for the contract between the DOE and LMSC and a new subcontract between LMSC and KSI.

5.18 "Tiling" Image Registration Algorithm

This section summarizes further testing that was done of the tiling algorithm for image registration.

A few cases were found in which false positives were detected by the new tiling algorithm but not by the older, more simple approach to image registration and so there was some concern that there might be some problem with the new approach.

Closer analysis of these cases showed that in fact the false positives detected were due to specular reflections from the drum that were not in the same location in the baseline and new images (because of small camera positioning differences for the two images). The reason that these specular reflections had not shown up as change regions in the older approach to registration was basically a matter of chance. The older approach performed registration by translating the new image horizontally and vertically so that it registered with the new image in a rectangular region around the label. With this approach there is a chance that the combination of this translation along with other sources of misregistration (e.g. rotation about the optical axis) could cancel out so that the specular reflection ended up in the same location in the shifted image as in the baseline image.

So in conclusion, we do not know of any problems with the current implementation. It correctly detected some changes which the older approach did not. It just happened that these changes were false positives due to specular reflections.

5.19 Image Processing Consultation.

Prof. Lowe, University of British Columbia (UBC) developed the core photogrammetric software that it is used in the Eagle Eye™ program, and he has considerable experience in the area of the computer vision and object recognition. Jeremy Wilson and Gloria Chow of KSI met with Prof. Lowe for several hours on July 18 to discuss some of the challenges of the drum inspection problem.

On the topic of specular reflection, Prof. Lowe noted that it is common for computer vision projects to encounter difficulties in this area. An important observation about specular reflections is that the color of the reflection is the color of the *light source*, not the color of the *surface* (except for the case of a reflection off bare metal). This is due to the physical mechanism involved in specular reflection. This observation naturally raises the point that a light source with a special color signature could be used to assist with automatically locating specular reflections. The color signature could be created by momentarily moving a color filter in front of the light).

Also discussed was the topic of establishing barrel pose. Prof. Lowe's first point was that he believed that using an optical target (such as the Eagle Eye™ label) on the barrel, pallet, or floor was probably the most reliable method. However we did discuss alternatives because of the possibility that establishing such targets may not prove operationally feasible. It was noted that the limited degrees of freedom of the IMSS platform might be used to advantage in constraining the numerical solution of barrel pose from barrel features. It may be necessary to store two or more views of the barrel from slightly different perspectives when establishing the baseline data.

5.20 Integration Plans

The following general approach to ABCD (Automated Baseline Change Detection) and IMSS (Intelligent Mobile Sensor System) integration was agreed to by Lockheed Martin Missiles & Space (LMSC, Palo Alto), Lockheed Martin Astronautics (LMA, Denver), and Kinetic Sciences, Inc. (KSI).

1. For ABCD Phase 1 continue to use Eagle Eye™ system for pose determination.
2. LMA to provide KSI with IMSS camera characteristics,
   i.e., lens focal length, camera type, camera calibration data..
3. KSI to provide LMA with at least fifteen Eagle Eye™ labels.
4. LMA collects about 10 images of each label using normal IMSS missions.
   Barrels at various tier levels and aisle positions will be measured.
5. The IMSS images will be transmitted to KSI to determine
   IMSS nominal position repeatability as presently operated.
6. LMA sends to LMSC the upper portion of the IMSS mast for use with the
   LMSC R2X testbed to establish IMSS image collection and
   change detection with the ABCD system. LMA personnel travel to
   LMSC to assist in the integration and testing.

7. LMSC sends to LMA the ABCD system for deployment system testing and demonstrations. LMSC personnel travel to LMA to assist in the integration and testing.

No substantive changes to the contract statement of work (SOW) are required, although emphasis and level of effort are changed among tasks. The interface requirement in Task 4 regarding the Generic Intelligent System Control (GISC) is superseded by IMSS interface requirements. Deliverables will be delivered to LMA for use by IMSS Phase 3 and ABCD Phase 2 tasks.

Concurrently, testing and development of the new tiling method of image registration and color camera image processing will continue to provide change detection in the IMSS system.

5.21 Requested Time Extension

A three month no-cost time-extension request was prepared for transmittal to the DOE. The reason for the request is that the Lockheed Martin Missiles & Space (LMSC) Automated Baseline Change Detection (ABCD) project is being integrated with the Intelligent Mobile Sensor System (IMSS) project at Lockheed Martin Astronautics (LMA), Denver, Colorado. This has required changes to the image processing software and to the mobile platform used for Phase 1 tests and demonstrations. Corresponding test plans, tests, and the Phase 1 Topical Report were delayed.

The advantages to the DOE are significant. The integration of these two DOE and Lockheed Martin projects is very cost effective and provides more capable, earlier, and lower-cost functionality than originally planned. The ABCD adds desired functionality to the IMSS system without duplicating any work with respect to mobile test or demonstration platform. Sections of the IMSS platform will be used in the ABCD testbed for early integration and full-function fielding. Direct and early use of the IMSS hardware is expected to result in an overall cost savings for the ABCD project.

As mentioned above, no substantive changes to the contract statement of work are required, although emphasis and level of effort are changed among tasks. The interface requirement in Task 4 regarding the Generic Intelligent System Control (GISC) is superseded by IMSS interface requirements. Deliverables will be delivered to LMA for use by IMSS Phase 3 and ABCD Phase 2 tasks.

5.22 Image Registration

Gloria Chow of Kinetic Sciences, Inc. (KSI) accompanied Shanon Grosko of Lockheed Martin Aeronautics, Marietta, GA, on a recent visit to Barrodale Computing Services in Victoria, BC. Of particular interest to the ABCD project was their work on image warping. We discuss here image warping and our impressions of the relevance to the ABCD project of Barrodale's software.

Image warping is an image restoration technique targeted at correcting non-linear geometric distortion. Typical causes of non-linear geometric distortion are optical system characteristics and perspective changes. The first is not a major concern as long as the same optical system (i.e.. lens, camera and frame grabber) is calibrated for both the baseline and subsequent inspection images. The distortion pattern could be corrected before image subtraction. Also of importance is the geometric distortion due to perspective changes. Because of mechanical limitations and slight sensor errors, it is almost inevitable that images taken at different times will be subject to slight perspective changes. The following discusses this second aspect of image correlation.

KSI has already implemented a tiled correlation and subtraction technique that addresses precisely this perspective distortion problem. Under this technique the images are divided into a number of slightly overlapping tiles, and a form of image correlation is then applied on a tile-by-tile basis to find a local match between the baseline image and the new image. The correlation result is used to shift and subtract the non-overlapping portion of the tile so as to ensure each pixel is manipulated once and once only. While the correlation and image shifting techniques are themselves linear, because they are applied separately to each tile, they do collectively approximate a non-linear correction process. Furthermore, it should be noted that while a smaller tile size may tolerate a higher degree of non-linearity, it also decreases the available amount of textural information and thus the confidence of the correlation result. The size of the tile has therefore been carefully designed to optimize both of these measures in our current system. However if even bigger errors in camera positioning are to be tolerated, a more complete non-linear image restoration technique, such as image warping, may be needed.

In its simplest form, image warping can be defined as follows :

> Given two input images, A and B, each with a set of fiducial points marking a one-to-one pixel correspondence between the two images, the process of image warping performs a geometric transformation on B, one of the input images, so that the location of the fiducial points of the transformed image B' will map exactly that of the other input image A.

This geometric transformation typically involves a spatial remapping of pixels on the image plane based on mapping function derived from the fiducial point correspondence and a gray-level interpolation to determine the appropriate intensity to be assigned to pixels in the spatially transformed image.

A potential integration idea is to treat each image tile as a virtual control point, the tiled correlation step will yield a one-to-one mapping of these virtual control points upon which image warping can be performed. Currently, the tiled correlation step is applied somewhat indiscriminately over the entire image. The assumption is that if the matching is poor, there is probably very little texture and a slight shift of a uniformly illuminated area will not produce noticeable difference and therefore is not a big concern. Yet, in order to use the tiled correlation technique in conjunction with image warping, one must examine the quality of the correlation measures more closely to avoid erroneous control points. This can be done as a pre-processing step analyzing the baseline image to extract interesting regions (i.e.. highly textual area) over which correlation can be applied confidently. Alternatively, one can perform statistical analysis on the correlation response to determine how "good" a match has been obtained, i.e.. is it significantly or just marginally better than the alternatives. Both methods will allow maximum reuse of existing software and the significant software investment will reside with implementing an efficient and robust image warping algorithm. And it should be noted that while image warping is a conceptually simple process, to achieve an accurate realistic mapping, one often has to use a higher order or surface spline mapping function. The derivation and application of such complex mapping function tends to be complex and computationally expensive. It was under this context that the Lockheed-KSI team visited Barrodale Computing Services in Victoria to inquire about "Spider Warping", their commercial image warping software.

Barrodale's Spider Warping software provides a computationally efficient frame work for computing and evaluating spline-based warping functions. In fact, they have extended the purely fiducial-point-based image warping to incorporate more flexible matching of curves to generate additional control points for warping. This is particularly useful if the number or distribution of fiducial points are not adequate to characterize the underlying non-linear distortion function, then curve points can be supplemented and used just like fiducial points. The difference between curve points and fiducial points is that if there does not exist a readily available one-to-one mapping between the two images, the warping software must extract, based on image characteristics, a match between image curves (which can be slightly deformed between the two images) and resample the curves to produce a one-to-one mapping of curve points. The current Barrodale software is completely operator-driven. Both the input fiducial points and spider curves must be input manually. Conceptually, this could be automated by a preprocessing layer such as the correlation-based virtual control point concept suggested earlier. However, further work would be needed in order to construct the spider curve map and fully utilize the capability of Spider Warping. Since we have some control over the location and number of virtual points (i.e.. tiles) generated, it is unclear if the additional spider curve capability is needed in our system. A more immediate question regarding the applicability of Spider Warping is of integration. The current implementation of Spider Warping has been done in FORTRAN under SunOS UNIX, whereas our frame grabbing and image processing platform is the Macintosh. Unless we are to spool the image off for off-line analysis, sending images back and forth between a Macintosh and a Sun UNIX box is not an ideal solution. Ian Barrodale, president of Barrodale Computing Services has however indicated that it is relatively straight forward to port Spider Warping to the Macintosh environment.

5.23 Enhancements to System Software

Larger camera positioning errors are anticipated for the IMSS platform (up to 2 cm). This adds additional complexity to the image registration process in two ways: we can no longer depend on the intensity calibration pattern appearing in the same location in each image, and the overall shift between the baseline and new images is much greater which can reduce the robustness and speed of the tile based image matching if all we do is simply search over a larger area.

The intensity calibration pattern is a group of squares on the label which have a range of gray levels from white to black. This pattern is the basis for normalizing the image intensity of the new image so that changes in lighting are less likely to induce false detections of change between the baseline and new image. To date we have been able to rely on this pattern being in the same location in the image, plus or minus a few pixels. However this simplistic method breaks down as soon as the shifts become larger. Fortunately the solution is straightforward. Eagle Eye™ already has internal knowledge of the position of the label in the image (which it uses to determine the spatial position and orientation of the label). However image coordinate information was not previously part of the output data stream. We have now added two additional output stream options: the image coordinates of the origin of the label, and the bounding box that defines the part of the image containing the label. We are also adding to Eagle Eye™ the capability to set and query the output format remotely so that the correct set of output values is automatically configured. Now that the image coordinates of the label origin (i.e. the center of the label) are now available, the two further steps are required: the IPM (image processing manager) must be extended so that it can save the label location data in a file associated with each image, and the IPLab code needs to be extended to utilize this information in determining the location of the intensity calibration pattern.

The tile based image matching works well for small image shifts. However for larger shifts the search area for each tile has to be increased, with the result that speed decreases (proportional to the square of the search distance) and robustness decreases (because there is a statistically greater chance that the tile will be incorrectly matched, especially if the image within the tile has little texture or repeating patterns). The solution to this problem is to make better use of the *a priori* knowledge we have of the imaging situation. Firstly, we can get a good estimate of the overall shift by using the label position information provided by Eagle Eye™ (as discussed above). Secondly, we know that neighboring tiles should shift by similar amounts. On this basis we have begun implementing improvements to the tile based change detection. The initial estimate of the shift for the central tile (corresponding to the center of the label) will be based on the information from Eagle Eye™. The tile correlation process will begin with the center tile and work outward to the periphery of the image, propagating the shift information from the inner tiles outward so that each individual tile only needs to perform a small local search, maintaining both speed and robustness.

5.24 IMSS Platform Testing

The first step in testing the positioning repeatability of the IMSS platform using Eagle Eye™ is to establish camera parameters and verify that the Eagle Eye™ drum label can be reliably detected. Toward this end, a new drum label was designed based on camera specifications provided by Eric Byler (LMA). After some discussion it was decided that the best camera to use would be the central b/w camera rather than either of the color cameras. This is because the b/w camera has a higher effective resolution than the single CCD color cameras, allowing the Eagle Eye™ faces on the label to be smaller. The central camera also looks at the label head on rather than from one side which should improve the range of positions over which the label can be seen.

The new label has the same basic two-face design as the labels in use at LMSC (Palo Alto) but has smaller faces (2.24" versus 3.2"). This size of label is distinctly less obtrusive than earlier designs. Two sample labels and an Opti-CAL calibration target have been sent to Eric Byler so that sample images can be captured. Ray Rimey will be running the tests. As soon as calibration and reliable tracking are verified, more labels will be prepared and sent so that the positioning repeatability test can be run.

The process of producing the drum labels has been refined somewhat over earlier labels. Previously the Eagle Eye™ face patterns needed to be physically cut and pasted onto a label template. We have found that it is straightforward to perform a softcopy paste of postscript versions of the face patterns directly into the drawing program (Aldus Superpaint) used to produce the label template. This results in much more accurate face positioning and easy repeat printing. When larger numbers of labels are needed we can fully automate this printing process. However for now this softcopy method is quite adequate for small numbers of labels.

5.25 Tiling for IMSS

Initial tests of the new image-registration algorithms (tiling) resulted in problems with repeating patterns in images. In the initial approach, tiling started from the center of the image and worked toward the edges, correlating and registering features as it progressed. But if there is a high probability of a feature being repeated near the center and if the camera view is offset by a centimeter or so, as is expected in the IMSS system, then the initial correlation may start by misregistering two different features as the same feature.

In addition, with a few centimeters of variation in the IMSS repositioning, the location of the intensity-normalization grid is similarly displaced in the image and intensity normalization could be in error.

Both of these issues were addressed. The new approach will be to locate the intensity normalization grid for each and every image as a variable function of the position of pose of the barrel, i.e., as a function of the Eagle Eye™ markers. The location of this grid then also identifies identical features which must be coincident in baseline and inspection images. Thus tiling registration will proceed from that position and radiate outward without necessarily starting in the middle of the images.

5.26 IMSS Experiments

We discuss here the data collection and testing performed at the IMSS lab in Denver during the week of November 27th. The purpose of this trip was to collect a substantial data set of ABCD drum images using the IMSS platform and fully exercise the ABCD software required for batch processing of these images. It was also an important opportunity to learn more about the platform functionality and performance that will be required to operationally support automated baseline change detection. Longer term integration issues were also an important discussion point. The visit was supported by Eric Byler and Ray Rimey of the IMSS team.

The first two days were focused on set up. The ABCD software was installed and tested, the network links between the machines used in the test were established and tested, and the sensor suites were calibrated. One of the lessons learned here was the need for a comprehensive calibration procedure covering the many variables of the imaging situation (including focus, iris, shutter speed, white balance, convergence angles, tilt angles, and lighting). In an operational setting we believe it will be important to have as many as possible of these variables under computer control.

The last three days focused on data gathering, and batch processing of selected images to test the ABCD software and refine processing parameters (there was insufficient time to process all the data during this week). Altogether three baseline runs and five change detection runs were completed using the top and bottom sensor suites of the IMSS. One aisle was set up with 10 labeled drums, and a second aisle was set up to simulate change detection on B-25 storage boxes. Following a baseline run, various forms of simulated changes were made including various colored dots, white powder, water, and (in the case of the boxes) various kinds of scratches and punctures. Altogether 464 images were captured. Positioning repeatability data was collected using graph paper affixed to the floor in the aisle. Video footage of the testing was also taken.

Once we have completed processing of this data we will have learned a lot about the operational issues that impact on the effectiveness of the automated baseline change detection concept, and we believe the results will underscore the importance of change detection as a valuable precursor to other forms of visual inspection.

5.27 Preliminary Analysis of Change-Detection Deployment System Data

We discuss here the preliminary results from analysis of the image data collected at the IMSS lab in Denver during the week of 27 November . This discussion applies to both Task 4.0, Change-Detection ER&WM Field System Compatibility Verification, and to Subtask 5.4 Field System Requirements Assessment for Phase 2.

The change detection software developed for ABCD includes provision for subtracting the ambient image (i.e. the image taken with no additional lighting) from the fully illuminated image (i.e. the image taken with the robots lights turned on). The purpose of this step in the processing is to remove any lighting effects due to changes in the ambient light conditions (which we cannot control). While this approach is sound, it does depend on the fully illuminated image being significantly brighter than the ambient conditions. The IMSS platform does not currently allow dynamic control of the robots illumination (apart from simply switching on or off all the lights). As a result, there are cases (e.g. on the top of the stack close to the overhead lights) where the ambient and fully illuminated images are not significantly different. Subtracting out the background light in such cases reduces significantly the contrast in the resulting image. Because the ambient conditions in the IMSS lab were very consistent, we recommend that ambient subtraction not be used for this dataset because of the loss of contrast. In an operational setting it will be important for the mobile platform to have better control of the lighting and camera parameters (iris & shutter speed).

The IMSS platform currently has a problem with pattern noise in the images (faint diagonal bands in the image), due to some unfiltered electrical noise source on the platform (possibly the DC-DC converters in the mast, but there are a number of other candidates given the distance from the camera to the frame grabber). This pattern noise shifts from image to image. This is a problem for the edge-based correlation technique that we use to register a baseline and new image because in areas of the image with few features the correlation tends to lock onto the noise rather than genuine image features. We have been using a Laplacian of Gaussian filter (known as an "LoG" filter), but this noise problem led us to experiment with several alternate edge detectors supported by IPLab to see if greater noise immunity was possible. As a result we have switched to using the Sobel edge detector, which is less sensitive to this noise and is actually faster. We don't believe this will impact on detection of 1/4" size features, but won't know for sure until more systematic testing has been done. In the longer term, we can see that the current tiled correlation method would benefit from further improvements to the way that results from well featured areas are propagated (currently propagation occurs only from the center of the label, outwards).

Eagle Eye™'s performance on the first baseline and inspection runs did not appear to be particularly good until a closer analysis was performed. It turned out that Eagle Eye's edge contrast threshold had been set too low (perhaps while experimenting with some low contrast images). Setting the contrast threshold correctly improved its performance on properly illuminated images. The remaining failures in these two test sets were all due to illumination problems: either image saturation (too much light which can lead to blooming around edges), or too little light (in some early runs a camera's iris setting was inadvertently bumped resulting in dark images; these images will be rejected from the test set).

5.28 Change-Detection ER&WM Field System Compatibility Verification

We summarize here the actions taken to collect DOE ER&WM operational requirements for barrel inspection in warehouses. This applies to both Task 4.0, Change-Detection ER&WM Field System Compatibility Verification, and to Subtask 5.4 Field System Requirements Assessment for Phase 2.

As stated in the Section 4, on 30 November Peter Berardo, LMSC, attended the ARIES (Autonomous Robotic Inspection Experimental System) Phase 2 demonstration at the University of South Carolina, SC (previously reported). And on 7 December Carl Adams, LMSC, and Guy Immega, KSI, attended the SWAMI (Stored Waste Autonomous Mobile Inspector) Phase 2 Phase 2 demonstration at the DOE Fernald Laboratory.

With the previous attendance by Berardo and Immega at the IMSS (Intelligent Mobile Sensor System) Phase 2 demonstration at Lockheed Martin Astronautics, Denver, all DOE barrel inspection systems currently underdevelopment have been observed for ABCD field system compatibility and eventual operations.

Also, as stated in Section 4, on 30 November Peter Berardo, LMSC, participated in the DOE barrel-inspection "bake-off" planning meeting at the University of South Carolina, SC (previously reported). And on 7 December, Carl Adams, LMSC, and Guy Immega, participated in the DOE barrel-inspection "bake-off" planning meeting at the DOE Fernald Laboratory.

With the 20 April participation by Berardo and Immega in the DOE and contractor meeting coincident with the IMSS (Intelligent Mobile Sensor System) Phase 2 demonstration at Lockheed Martin Astronautics, Denver, the ABCD project has participated in all recent DOE and contractor barrel inspection meetings. These meetings serve to establish the DOE ER&WM field system requirements for barrel inspection and the compatibility of the ABCD system with those requirements.

Finally, as part of Task 3, the ABCD system was partially integrated with the IMSS system to conduct inspection experiments in the Lockheed Martin Astronautics laboratory in Denver.

The results of all three robot Phase 2 demonstrations, three requirements planning meetings, and our direct experience with integration of ABCD and IMSS lead to the following general conclusions:

(1) Warehouse and barrel changes to be operationally and routinely detected are within the capabilities of the ABCD system, as least as determined in Phase 1 and in the summary requirements of the 7 December meeting at Fernald;

(2) Present mobile systems -- IMSS, SWAMI, and AIRES -- do not provide sufficient lighting control for ABCD, but all easily could do so.

(3) Each mobile system is sufficiently different so that no single ABCD integration scheme will directly work for more than one system, but each mobile system is sufficiently modular and uses typical interfaces so that integration is fairly straightforward for any system;

(4) Repositioning accuracy for each mobile system is approximately the same and the ABCD system can work within those limits, provided that adequate visual fiducials are used, as now accomplished directly with the ABCD labels;

(5) Following the mobile-system bake-off, a composite system should be specified to include modular components, defined interfaces, repositioning accuracy, and lighting control.

6.0 Assessment of Current Status

At the end of Phase 1 the ABCD (Automated Baseline Change Detection) project has met all of its primary objectives in the Statement Of Work (SOW) and is under budget by about 15%.

But the accomplishments go beyond what was planned. Because of the early integration of ABCD with another DOE project, namely the IMSS (Intelligent Mobile Sensor System) project, overall DOE capabilities are ahead of expectations. Due to early integration, the ABCD project spent less on intermediate test hardware and more on enhancing the robustness of change-detection. These enhancements are needed to be compatible with IMSS and will also enable more efficient integration with the AIRES and SWAMI mobile robot platforms.

In meetings with DOE and contractor personnel involved in robotic barrel inspection, it is clear that overall requirements are still evolving. But ABCD has helped move other projects toward integration with ABCD to provide the DOE with additional capabilities. The robotic barrel-inspection "bake-off" planned for early 1997 at Fernald is actively involving the ABCD toward this end. Phase 2 of ABCD is needed and current Phase 2 contractual plans are valid and include those tasks required for fielding an ABCD system and also for supporting the DOE "bake-off".

Finally, an important aspect of the current status is the extremely good relations that exist among all parties to the ABCD project. The METC CORs (Contracting Officer Representatives) Cliff Carpenter and Kelly Pearce have demonstrated superior leadership of the barrel inspection projects. Their alertness to DOE requirements, synergistic opportunities among contractors, and objective of fielding a capable system inspire a high degree of respect and cooperation among all participants. In addition, Brack Hazen, DOE Fernald, has become a very positive effective laison among warehouse operators, METC, and contractors; his interest and cooperation is greatly appreciated.

Kinetic Sciences, Inc. (KSI), the LMMS subcontractor, serves key roles in high-precision pose determination and image processing. Guy Immega, Dr. Jeremy Wilson, and Gloria Chow demonstrated great expertise and were a genuine pleasure to work with.

Working with our new sister company, Lockheed Martin Astronautics in Denver was also very rewarding. Eric Byler and Ray Rimey have helped greatly with the integration of ABCD with IMSS, both in support of DOE objectives and because of conviction that together the two systems provide needed capabilities. We look forward to working with them in ABCD Phase 2.

As program manger and principal investigator, Dr. Peter Berardo has enjoyed the extremely capable and dedicated efforts of Carl Adams and Dr. Bill Dickson, his colleagues in the LMMS Automation and Robotics Laboratory. Their ABCD experience, perspectives, and enthusiasm assure a successful Phase 2.

7.0 Plans

Phase 2 plans are discussed in the following sections:

- 7.1 Basis for Phase 2 Plans
- 7.2 Phase 2 Contractual Plans
- 7.3 Changing Planning Requirements
- 7.4 Changing Technical Requirements.

7.1 Basis for Phase 2 Plans

In Phase 1 there was the opportunity for early integration of the ABCD system with another DOE robotic barrel inspection program, namely the Intelligent Mobile Sensor System. Both IMSS and ABCD are METC projects and they are now, since the Lockheed and Martin Marietta merger, in different companies of the same Lockheed Martin Corporation. This integrated approach will effectively field the benefits of ABCD much earlier than originally planned by either the DOE or Lockheed.

Additionally, the METC CORs took a strong lead and coordinated DOE operational inspection requirements among DOE warehouse operators and the four DOE barrel-inspection projects.

Thus, there were two significant changes in direction during Phase 1 -- project integration and requirements integration. Nevertheless, for Phase 1 the ABCD Objectives, Statement Of Work (SOW), and Work Breakdown Structure (WBS) did not change. Only emphasis among Subtasks changed. This demonstrates highly consistent understanding between the DOE and Lockheed Martin of the inspection problem and objectives.

Similarly, no changes are planned for Phase 2 at the Task level. Changes at the Subtask level will undoubtedly occur as ABCD and IMSS integration continues and as the DOE leads a "bake-off" competition involving all barrel inspection projects early in 1997.

Thus at the end of Phase 1, the plans for Phase 2 are unchanged and relevant elements of the original contract are presented here as the basis of Phase 2 plans.

7.2 Phase 2 Contractual Plans

The contents of this subsection are extracts from Section 1.0, Formal Objectives.

Objective (Contract) -

The objective of this contract is to apply robotic and optical sensor technology to the operational inspection of mixed toxic and radioactive waste stored in barrels, using automated baseline change detection (BCD), based on image subtraction.

Phase 2 (Task objectives)

The Task 7 objective is complete the reports as given in "Required Information for the National Environmental Policy Act (NEPA)."

The Task 8 objective is to build, integrate, field test, and evaluate a ABCD Field System for an operational DOE site.

The Task 9 objective is to manage Phase 2 to meet reporting, deliverables, budget, and schedule requirements.

Contractual Statement of Work

Objective (SOW)

The objective of this effort is to apply robotic and optical sensor technology to the operational inspection of mixed toxic and radioactive waste stored in barrels.

Phase 2 Scope of Work

Phase 2 will produce and operationally test a freely autonomous waste barrel inspection at a DOE site. The Phase 2 mobile field system shall integrate the ABCD sensor with an autonomous mobile platform in a manner which satisfies DOE operational and regulatory requirements for automated waste barrel inspection.

Phase 2 Tasks To Be Performed

TASK 7. INFORMATION REQUIRED FOR THE NATIONAL ENVIRONMENTAL POLICY ACT

The contractor shall prepare a draft report which provides the environmental information described in Attachment A2, "Required Information for the National Environmental Policy Act (NEPA)". This information will be used by the DOE to prepare the appropriate level of NEPA documentation for Phase 2 of the project. This draft report shall be submitted to the COR within sixty (60) days after contract award. DOE shall review the report and advise the contractor of the acceptability of the report or the need for additional information within thirty (30) days. The contractor shall submit a final report within two weeks of notice of acceptability of the draft report.

Until the NEPA review and approval process is completed the contractor shall take no action that would have an adverse impact on the environment or limit the choice of reasonable alternatives to the proposed action. The contractor is not precluded from planning, developing preliminary design, or performing other work necessary to support an application for Federal, State, or local permits.

TASK 8. FIELD TEST AND EVALUATION

The contractor shall build and integrate a field system prototype of the Change-Detection System to include an operational test and evaluation of an autonomous full function system at a DOE site. Prior to proceeding with this task however, the contractor shall prepare a test plan and forward it to DOE for review and comment.

TASK 9. PROJECT MANAGEMENT

The contractor shall manage the cost, schedule and technical elements of the Phase 2 effort. This task shall include project planning, oversight and reporting to the government, including subcontract management, if applicable.

The contractor shall prepare and submit reports in accordance with the Reporting Requirements Checklist and as applicable and described (in the original contract) in the Section D, DELIVERABLES. The contractor shall prepare and present briefings to the DOE as applicable and described in Section E, BRIEFINGS.

7.3 Changing Planning Requirements

Integration with IMSS and other projects raises issues about:

- Commonality of software and hardware
- Unique requirements and capabilities of each system
- The requirements, time schedules, and resources available for integration.

There are few specifics that can be addressed here since changing requirements lead to changing plans. But certainly part of fielding a capable ABCD system will be to participate and cooperate with the DOE and Fernald "bake-off" experiments among the various barrel inspection projects. As the requirements of these experiments evolve, so also may the requirements and detailed plans change for ABCD.

In more general terms, based on currently known DOE requirements and current inspection systems, there should be no fundamental integration problems. METC has taken the lead in establishing DOE operational requirements. Fernald has taken the lead in warehouse operational validation. And the ABCD, IMSS, ARIES, and SWAMI projects have been involved and are committed to fielding the most cost-effective systems. At this time DOE plans and individual project plans are still evolving toward a final field system. Traditional systems engineering, when applied to current requirements, current inspection systems, and planned changes will yield the most cost-effective solution.

As was learned in the ABCD project, plans may change. Fortunately the many options apparently available suggest real long-term savings for the DOE. All that is required is the commitment to carry forward individually proven capabilities to a mutual field system.

7.4 Changing Technical Requirements.

Integration with IMSS raises issues about several new requirements that were not originally planned for either the ABCD nor the IMSS projects. One positive result of performing inspection experiments with the Phase 1 ABCD change detection system installed on the Phase 2 IMSS platform was to bring to light the problems that will be encountered when trying to create a field ready barrel inspection system, initially with IMSS and potentially with other DOE projects. Many problems were encountered during this testing, and many areas for future work in creating a more useful inspection tool were identified. Attachment 3, Section 3.2.4 discusses in detail technical integration issues. We highlight those points here.

7.4.1 Software integration and portability

In order to create a truly integrated mobile inspection system, a much higher degree of integration must be achieved between the software for the IMSS control and for the ABCD control. The future software configuration will achieve two goals. First, a greater coordination between the IMSS Control process and the ABCD Control process will be achieved by combining them on a single platform. The second step in creating a more robust system software would be to port the ABCD image processing functions to source code. This will save time and improve the portability of the resulting code.

7.4.2 Lighting and Iris control

A significant limitation of the present system is that it does not have real time feedback between the ABCD image processing functions and the IMSS control and data acquisition processes. Several inspection images, particularly those for camera 1 and those for the B25 boxes, had an inadequate illumination level for tracking of the Eagle Eye™ barrel marker. Active control of the light level and iris would correct this problem.

7.4.3 Repositioning feedback

Similar to the problem with actively controlling the lighting, a truly integrated inspection system would have feedback from the ABCD image processing routines to actively reposition the IMSS base to better register the camera with the baseline position. This was successfully demonstrated in Task 2 using a fixed base manipulator, but requires a greater degree of software integration to achieve with the ABCD/IMSS system.

7.4.4 Video noise

The performance of the change detection was limited in many cases during testing on the IMSS platform by a high level of noise in the video signals. The noise made many images particularly hard to register, especially in low light conditions.

7.4.5 Processing Time

Making the ABCD change detection system a real-time sensor will require a significant increase in the processing speed of the image processing algorithms. Once the code is portable, it could be hosted on a faster platform. In addition, there are many areas where parallel processing could be exploited to speed up inspections.