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Automated Baseline Change Detection Phase I

Final Report

December 1995

Work Performed Under Contract No.: DE-AR21-94MC31191

For

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

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

By
Lockheed Missiles and Space Company, Inc.
Palo Alto, California

MASTER

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USDOE

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1000 Independence Avenue
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Lockheed Missiles and Space Company, Incorporated
3251 Hanover Street
Palo Alto, California 94304

December 1995

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 not 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.

WBS Element / Subtask 3.4 Deployment System Change-Detection Implementation

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

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 Implementation, 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.

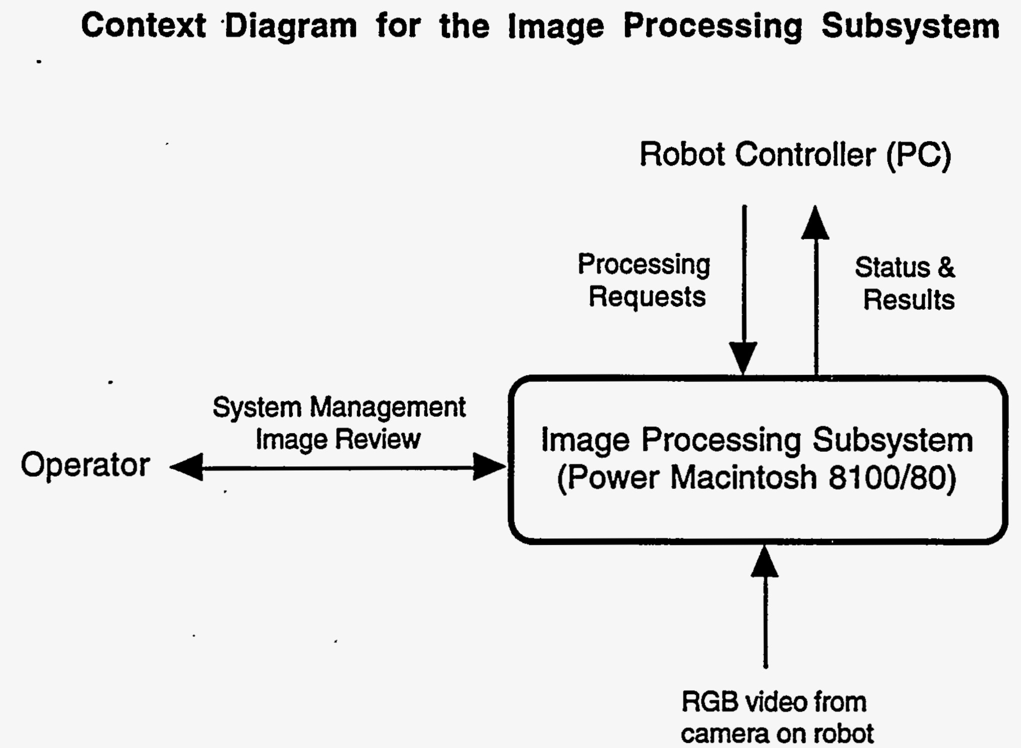


Figure 5.1: The image processing subsystem integrates camera calibration, image collection, and change detection for the ABCD system.

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.

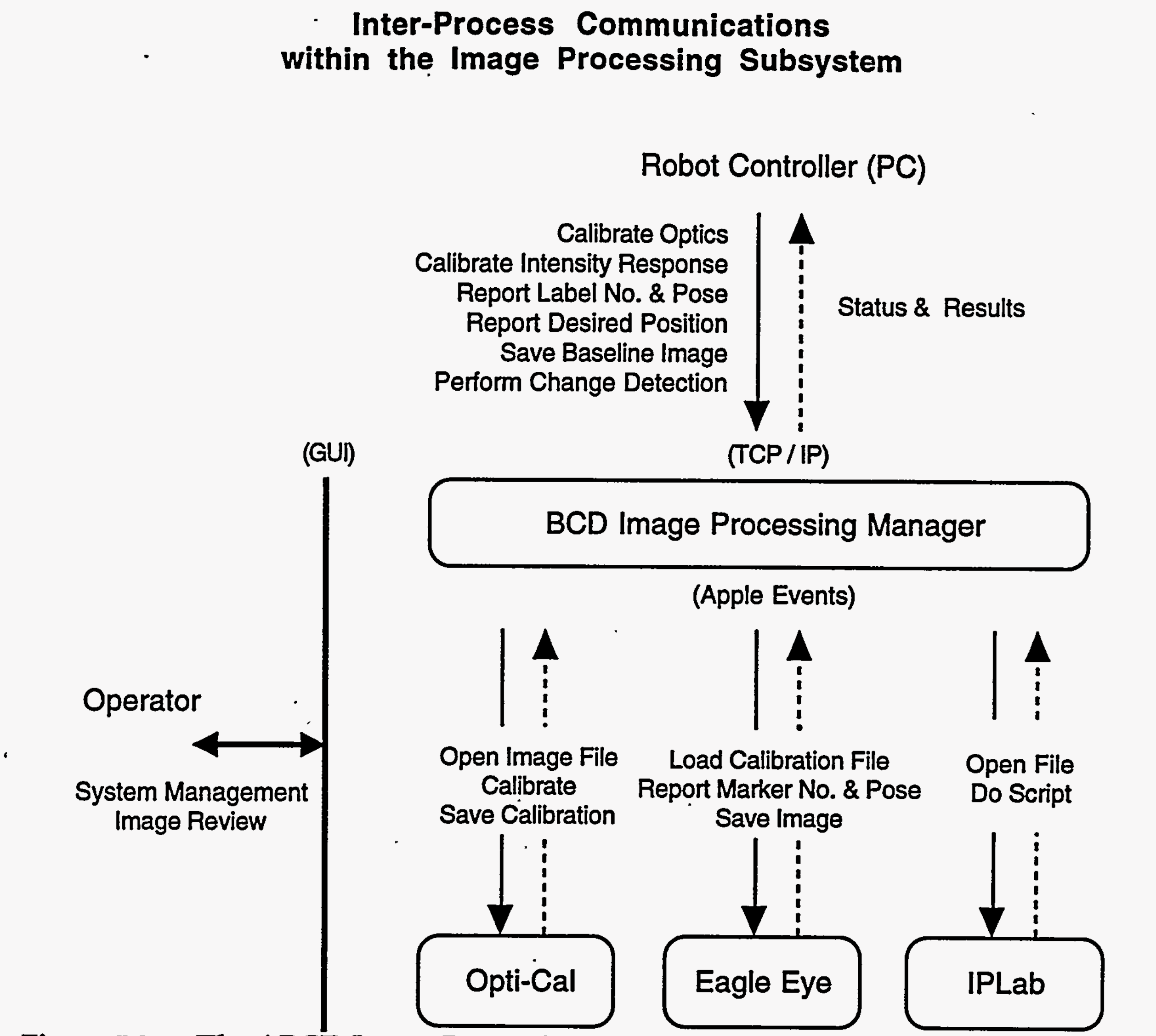


Figure 5.2: The ABCD Image Processing Manager coordinates the activities of the Image Processing Subsystem in response to operator commands or commands from the Robot Controller.

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).

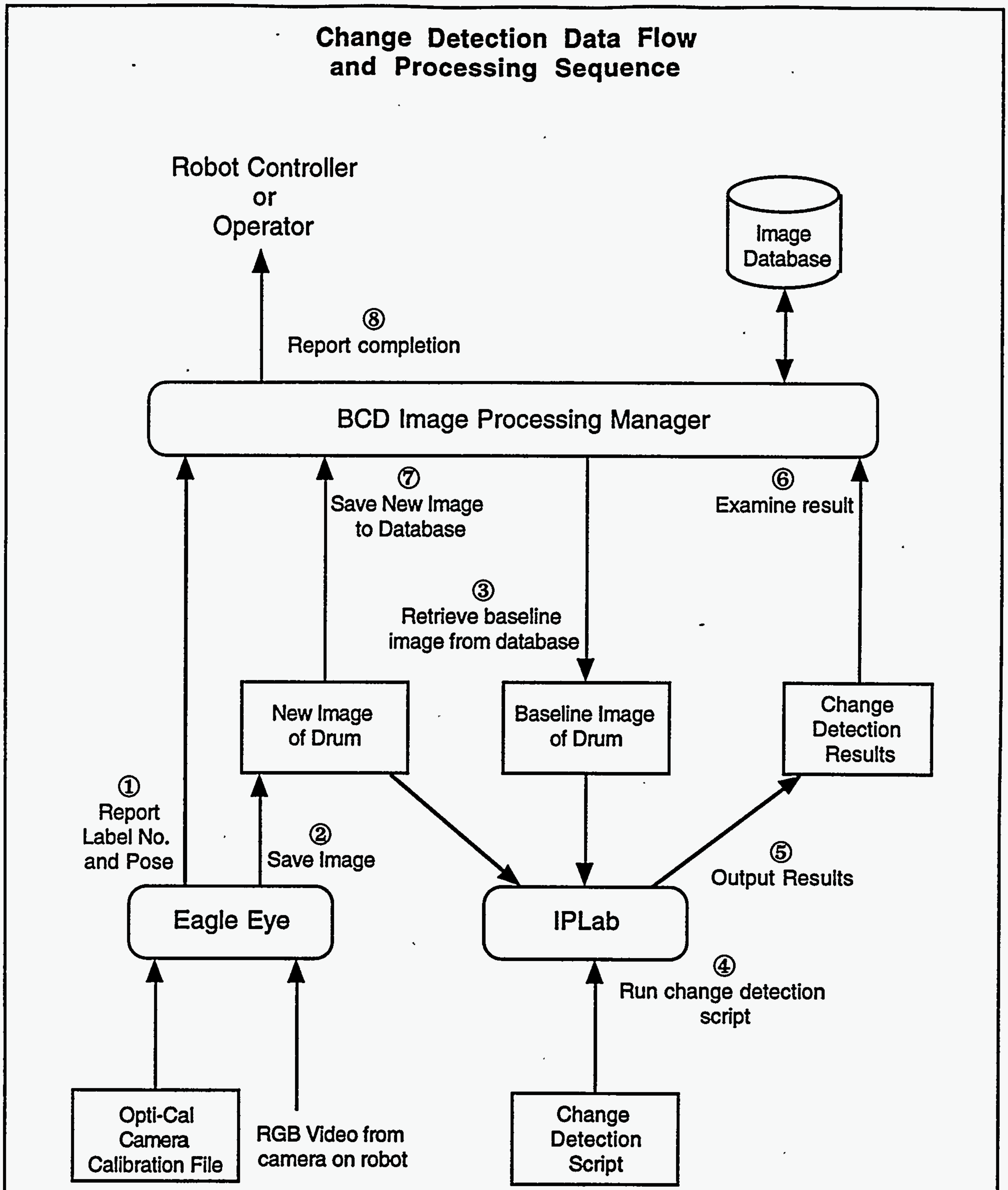


Figure 5.3: The ABCD Image Processing Manager controls each step in the change detection process, and maintains the drum image database.

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.

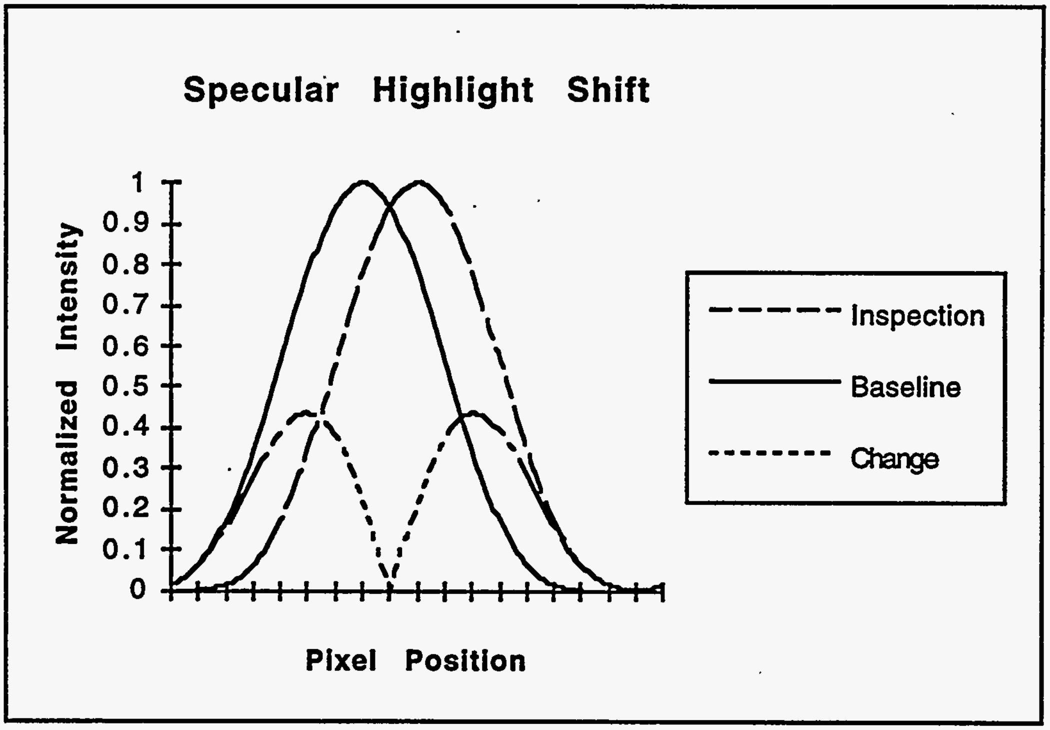


Figure 5.4. Detected changes may be due to spatial shifts of specular reflections.

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.

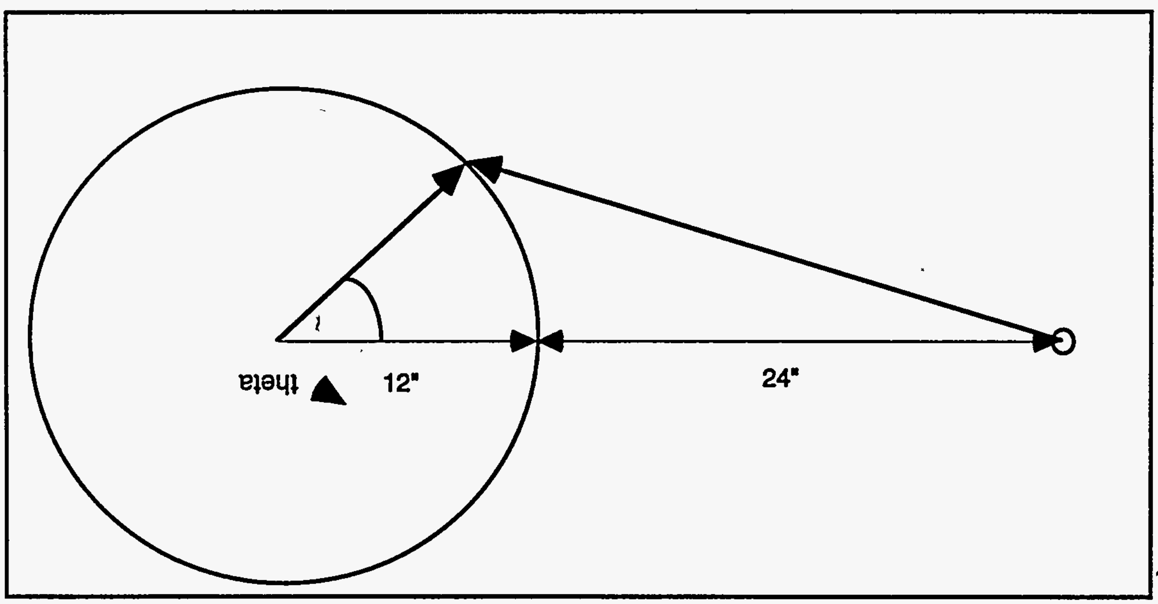


Figure 5.5. The amount of reflected light reaching a camera is dependent on the geometry of the illuminated object.

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.

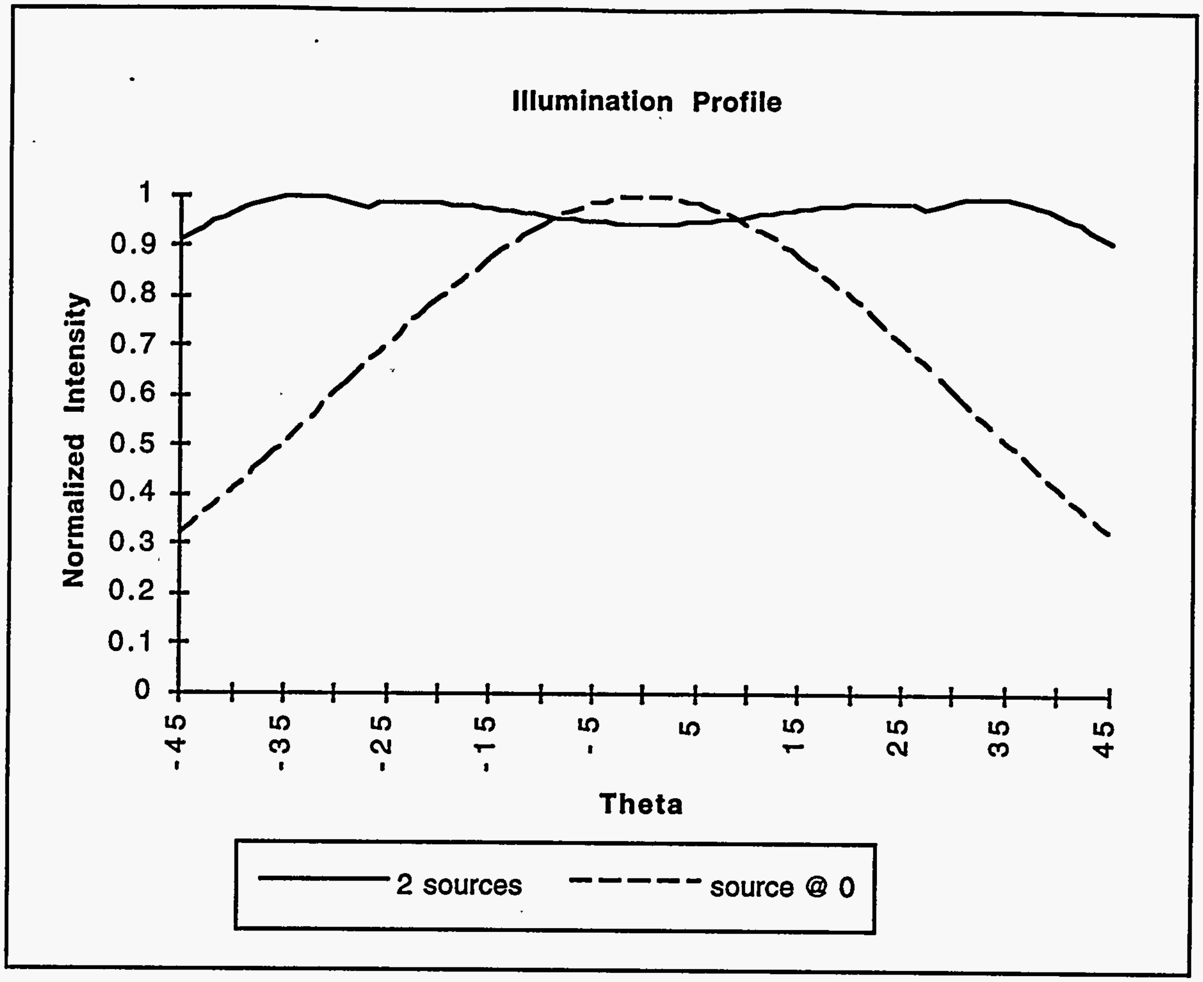


Figure 5.6. Relative incident intensity for one and two sources of illumination, which shows the importance of multiple light sources.

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.

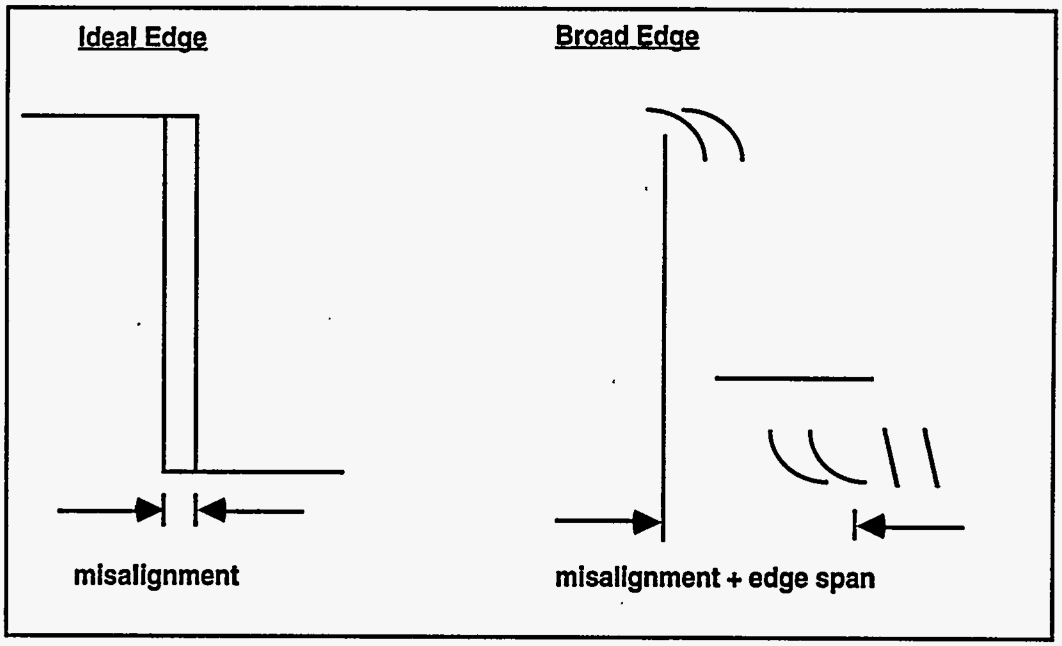


Figure 5.7. Detecting edges of changes depends on both pixel resolution limits and actual illumination fall-off.

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);

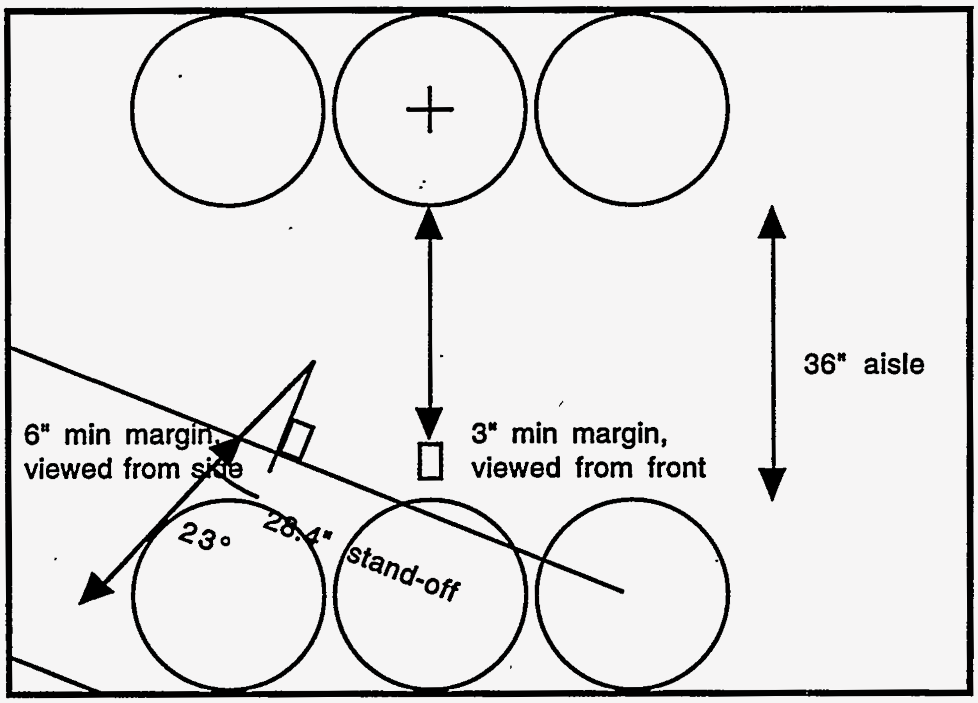


Figure 5.8. Multiple side views can increase the effective space behind a camera.

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.

Mapping: 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.

Recasting: 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.

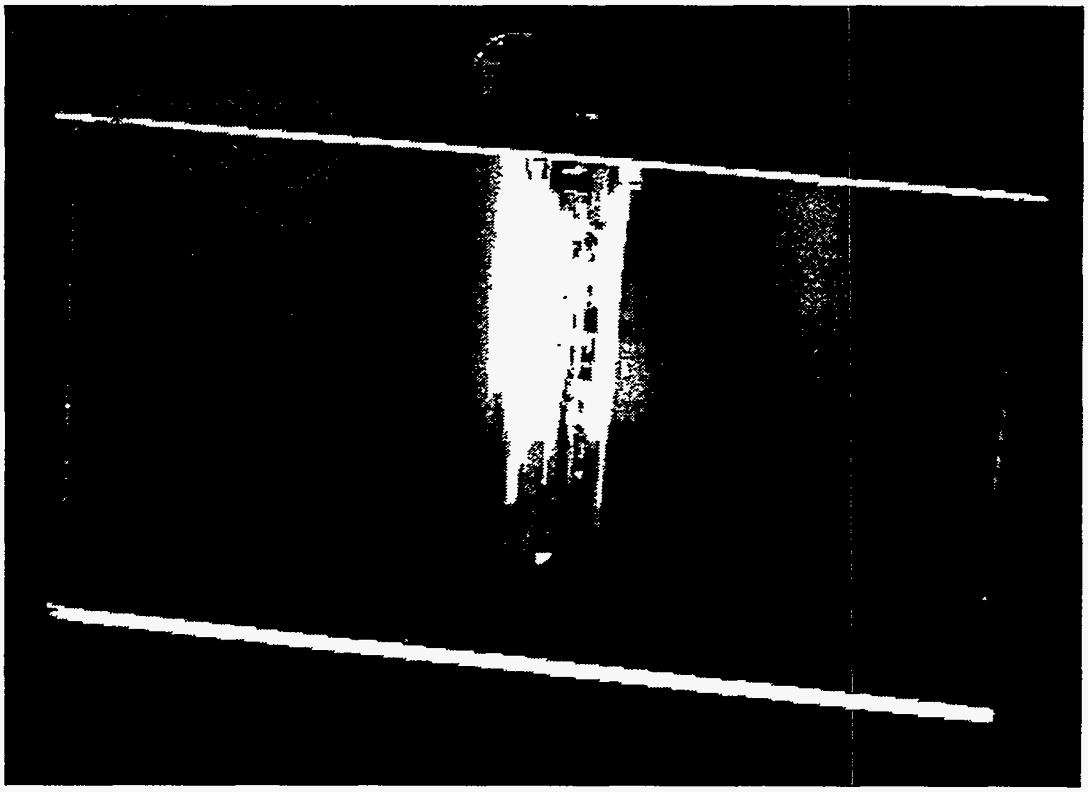


Figure 5.11. A shaped prototype reflector with one light source achieves more uniform lighting of a barrel than multiple light sources.

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.

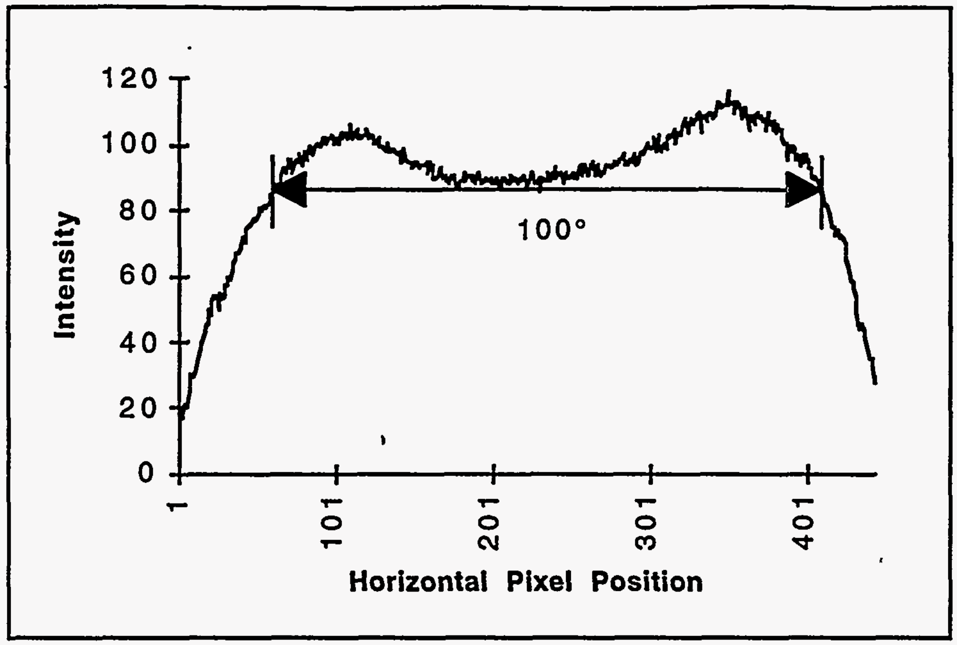


Figure 5.12: Example of Intensity Profile for Experimental Illumination Setup

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
AIRESA	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

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.

8.0 Attachments

A1. Task 1 Results, Change-Detection Performance Criteria Determination
A2. Task 2 Results, Change-Detection Application System Verification
A3. Task 3 Results, Change-Detection Deployment System Verification
A4. Task 4 Results, Change-Detection ER&WM Field System Compatibility Verification
A5. Task 5 Results, Phase 2 Field System Definition

PHASE 1 TOPICAL REPORT

ATTACHMENT 1

Automated Baseline Change Detection

Task 1 Summary Results

PHASE 1 TOPICAL REPORT

ATTACHMENT 1

Automated Baseline Change Detection

Task 1 Summary Results

A1. Change-Detection Performance Criteria Determination

The Task 1 objective is to empirically determine performance criteria for the BCD system. This objective is basically to determine a consistent set of values for:

1. Changes to be detected (size, location, and contrast)
2. Label marker (location, design, size)
3. Camera parameters (focal length, pixel size)
4. Camera positioning (precision, accuracy, position, orientation)

This objective was achieved and the results are presented here in the following sections:

1. Analysis of Geometry for Drum and Label Viewing
2. Label Size Analysis
3. Phase 1A (Task 1) Topical Report,
   "Performance Criteria and Expected Performance for Automated Baseline Change Detection"
4. ABCD Performance Criteria

PHASE 1 TOPICAL REPORT

ATTACHMENT 1.1

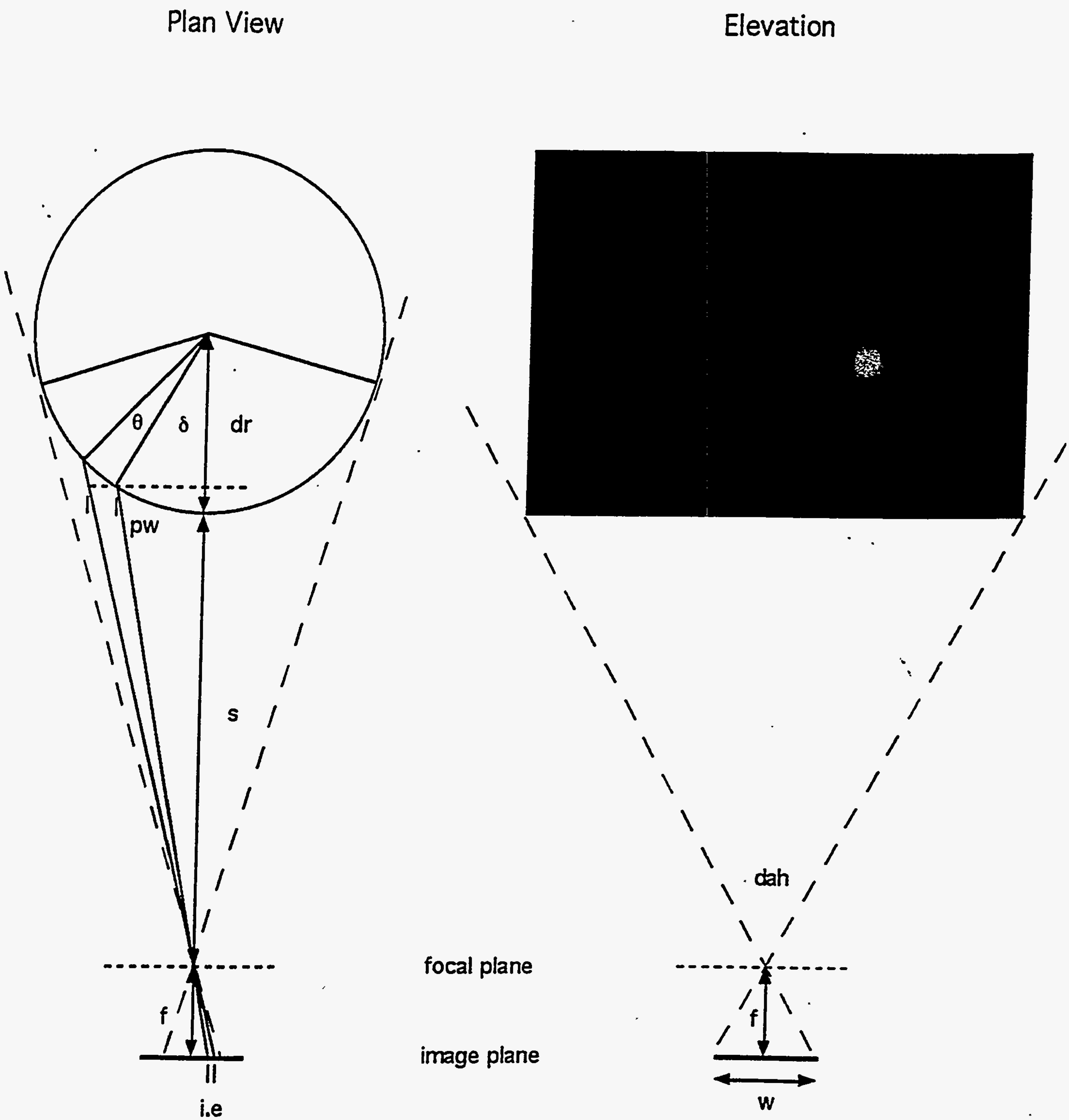
Automated Baseline Change Detection

Task 1 Summary Results

<u>Analysis of Geometry for Drum and Label Viewing</u>

(Presented on the next page in original format.)

Analysis of Geometry for Drum & Label Viewing



PHASE 1 TOPICAL REPORT

ATTACHMENT 1.2

Automated Baseline Change Detection

Task 1 Summary Results

Label Size Analysis

(Presented on the next page in original format.)

Label size analysis 11/14/94

Drum height:	**dh**	87.63	cm	**34.5**	**inches**
Drum diameter:	**dd**	57.785	cm	**22.75**	**inches**
Drum radius:	dr	28.893	cm	11.375	inches
Drum circumference:	dc	181.537	cm	71.471	inches
Stand-off distance:	**s**	40.784	cm	**16.057**	**inches**
Drum angular height:	dah	1.642	radians	94.104	degrees
Drum angular width:	daw	0.855	radians	48.997	degrees
Interior grazing angle:	iga	1.143	radians	65.502	degrees
Coverage:		36.39%			
Lens focal length:	f	0.37	cm	3.7	mm
CCD Width:	w	0.795	cm	0.313	inches
CCD Width:	**p**	**768.**	**pixels**		
CCD Element Width:	**e**	0.001	cm	**10.352**	μm
Face image width:	**i**	**45.**	**pixels**		
Faces around drum:	**faces**	**8.**			
Face center offset angle:	**gamma**	0.393	radians	**22.5**	**degrees**
Face width (angle):	**theta**	**0.229**	**radians**	13.104	degrees
Face edge offset angle:	delta	0.278	radians	15.948	degrees
dt/st		0.316			
dp/sp		0.315			
Diff. of label angle and drum angle:		0.636	radians	36.45	degrees
Check:		OK			
Image position of drum side:		162.88	pixels from centre		
Image position of drum top:		384	pixels from centre		
Image position of inner edge:		67.729	pixels from centre		
Image position of outer edge:		112.899	pixels from centre		
Check:		OK			
Curvature depth:		0.752	cm		
Curvature ratio:		11.39%			
Face width (cm):		6.608	cm	2.602	inches
Face separation (cm):		16.084	cm	6.332	inches
Two-Face Label Width (cm):		29.3	cm	11.535	inches
Check:		OK			

PHASE 1 TOPICAL REPORT

ATTACHMENT 1.3

Automated Baseline Change Detection

Task 1 Summary Results

Phase 1A (Task 1) Topical Report,
"Performance Criteria and Expected Performance
for Automated Baseline Change Detection"

(Presented on the next 52 pages in original format.)

Executive Summary

Background

The purpose of Automated Baseline Change Detection (abbreviated as BCD) is to automatically inspect hazardous waste drums in a warehouse and bring to the attention of warehouse operations staff any drums which deserve closer inspection because of possible deterioration. The operational concept for BCD is an autonomous mobile platform with a camera that can be accurately positioned in front of a drum to view it from a consistent perspective on each successive inspection visit.

By automating the task of waste drum inspection, the risk of human exposure to toxic and/or low grade radioactive materials will be significantly reduced. It is also believed that computer image processing techniques will improve the reliability and consistency of detecting changes, while also alleviating the need to perform a mind numbing task. The drums are expected to be arranged four to a pallet, and stacked three high in aisles as narrow as 30 inches (76 cm). A single warehouse may contain as many as 7,000 drums which need to be inspected individually for deterioration on a weekly basis. Changes on the front of the drum as small as 1/4" (6 mm) with a contrast as little as 10% should be detectable.

This topical report presents the results of the BCD Phase 1A tasks. The chief purpose of these tasks was to determine the **performance criteria** for Automated Baseline Change Detection. Specifically we were tasked with determining the performance criteria and expected performance in four areas:

(1) the static sensor limits of barrel identification accuracy (i.e. how accurate and repeatable does the positioning of the camera need to be);

(2) the limits of spatial resolution for detecting changes (i.e. what camera and lens system is appropriate, and given this camera and lens, how small a change can be reliably detected using image subtraction, with a minimum of false positives);

(3) the limits in image contrast for detecting changes (i.e. what is the minimum change in contrast that we can reliably detect using image subtraction, with a minimum of false positives);

(4) the limits of stability with changes in the sensor system components (such as camera, lights, and frame grabber hardware).

Additionally, we were tasked with reviewing the options for attaching adhesive labels on waste barrels. KSI's "Eagle Eye" vision system uses the special pattern printed on the label to identify a drum and to accurately determine its position and orientation with respect to the camera. The existing Eagle Eye optical marker has been redesigned as an adhesive label that would partially wrap around the curved surface of the drum. A flexible encoding scheme for barrel identification has also been determined.

Summary of Accomplishments

The drum inspection problem was carefully studied from both analytical and experimental perspectives to gain a thorough understanding of the constraints on camera positioning and illumination. These constraints define the performance criteria that the Application System and Deployment System must meet or exceed in order to successfully achieve its purpose of autonomously inspecting waste drums.

The vision system used to sense the position of the camera with respect to the drum (KSI's Eagle Eye product) is a critical enabling component of BCD, and the expected performance of this system

Figure E.1: Performance Criteria vs. Eagle Eye Expected Performance for Camera Positioning Repeatability (3.2" faces, 4.3 mm lens, 640 x 480 image)

Camera Position Axis	X (left right)	Y (up-down)	Z (in-out)	Tilt	Pan	Roll
Repeatability Criteria for Change Detection	±0.15"	±0.15"	±0.2"	±0.8°	±0.8°	±0.5°
Eagle Eye Position and Pose Resolution	±0.03"	±0.03"	±0.08"	±0.4°	±0.4°	±0.2°

was also studied analytically and experimentally. This work verified that Eagle Eye exceeds the positioning repeatability performance criteria by two to five times, despite significant distortion introduced by the wide angle lens required to see an entire drum. The best choice for the size of the adhesive drum label was also established.

The first row of figures in Figure E.1 summarizes the performance criteria for the BCD system with regard to repeatability of camera positioning. It defines the largest error in positioning repeatability of the camera that can be tolerated without introducing false detections of change. The second row of figures in Figure E-1 is the expected repeatability performance of Eagle Eye (assuming a label placed on the middle of the drum, a 4.3 mm lens, and a 640 x 480 image). This second row of figures also serves as a lower bound on the repeatability of the camera positioning mechanism since there is nothing to be gained from making the resolution of this mechanism higher than that of the vision system. These experiments also showed that the Eagle Eye marker patterns on the label should be 3.2" square.

Results for a label placed at the top (or bottom) of the drum are reported in Section 5, and show that the expected performance is degraded in this case, mostly because of the effect of drum curvature, but also in part because of the effects of radial distortion and loss of focus in the periphery. If labels are to be placed high (or low) on some drums, further work may be needed to find a satisfactory label design for this position. Tests were also performed to determine how far away the camera could be from the nominal center position before Eagle Eye was no longer able to see both faces of the label. The tests showed that the mobile robots navigation system will need to be able to move the camera to within about 6" horizontally and 12" vertically of this center point before label reading and tracking will be reliable.

Our experiments with regard to spatial resolution show that a 1/4" diameter spot corresponds to a region approximately 5 pixels across in the image (reducing to 3 pixels in the visible periphery of the drum). We believe that spots of this size (3 to 5 pixels in diameter) can be reliably distinguished (using automated image processing techniques) from background noise and minor changes less than 3 pixels across.

Experiments on illumination requirements and image contrast did not produce as clear cut results as the other categories of experiment. The results indicate that the objective of detecting changes in contrast as low as 10% may be optimistic, with a figure of 15-20% being more reasonable (at 10% we expect that the number of false detections would be too high). These experiments also indicated that the illumination from the light source should not change by more than about 5% to avoid inducing false changes. A technique referred to as ambient subtraction was tested for removing variations in image intensity due to changes in (uncontrolled) ambient illumination. The results highlighted the need to develop an automatic technique for calibrating the CCD cameras light response characteristics because these need to be known in order for ambient subtraction to work well.

Our overall conclusion is that the technologies of optical marker tracking (Eagle Eye) and change detection, combined with an autonomously navigated platform, are especially well suited to the problem of waste drum inspection.

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1. Introduction: Problem Statement and Task Objectives

1.1. Problem Statement

The purpose of Automated Baseline Change Detection (abbreviated as BCD) is to automatically inspect hazardous waste drums in a warehouse and bring to the attention of warehouse operations staff any drums which deserve closer inspection for deterioration.

The drums are expected to be arranged four to a pallet, and stacked three high in aisles as narrow as 30 inches (76 cm). A single warehouse may contain as many as 7,000 drums which need to be inspected individually on a weekly basis.

Three key enabling technologies make the concept of automatically inspecting these drums practical:

- a mobile robot that can automatically navigate inside a warehouse;
- a vision system capable of locating a special label on each drum, using this label to identify the drum and to accurately determine the position and orientation of the label with respect to the robots camera;
- automatic detection of change between two images of a drum, taken from the same viewing point, using image processing techniques including automatic image registration, image subtraction, and feature extraction.

This topical report focuses on the second and third of these technologies. Several key requirements define the waste drum inspection problem from the point of view of camera positioning and change detection:

- detect changes as small as 1/4" in diameter with as little as 10% contrast in a color image;
- use a camera/lens combination with a wide enough field of view to see an entire drum in a single image given that the camera has to operate in an aisle as narrow as 30";
- be sensitive to changes in ambient illumination and some variation in the brightness of the light source on-board the robot;
- the camera positioning time should be no longer than 30 seconds per drum, and change detection time no longer than 10 seconds per drum (run in parallel with camera positioning for the next drum) in order to enable a warehouse of 7,000 drums to be fully inspected in a one week cycle. For a single robot this allows for 50% recharging time and 15% (25 hours per week) for contingency activities such as maintenance.

1.2. Task Objectives

The overall objective of the phase 1A tasks was to determine the performance criteria for Automated Baseline Change Detection, and to assess the expected performance for the vision subsystem used to sense the position of the drum (KSI's Eagle Eye product). We also needed to obtain preliminary results for the performance to be expected from the change detection subsystem.

Four specific categories of performance criteria were identified as requiring study during phase 1A:

(1) the static sensor limits of barrel identification accuracy (i.e. how repeatable does the positioning of the camera need to be);

(2) the limits of spatial resolution for detecting changes (i.e. what camera and lens system is appropriate, and given this camera and lens, how small a change can we reliably detect with a minimum of false detections);

(3) the limits in image contrast for detecting changes (i.e. what is the minimum change in contrast that we can reliably detect with a minimum of false detections);

(4) the limits of stability with changes in the sensor system components (such as camera, lights, and frame grabber hardware).

Additionally, we were tasked with reviewing the options for attaching markers on waste barrels. The existing Kinetic Sciences Inc. Eagle Eye marker needed to be redesigned as an adhesive label that would partially wrap around the curved surface of the drum. The optimum marker size and barrel identification number encoding scheme were to be determined.

As a general point, we were concerned with identifying any new or previously under estimated factors that might impact on the systems design and implementation.

1.3. Approach Taken To Assessing The Criteria

The general approach taken in each of the tasks was to first attempt to estimate the criteria analytically (i.e. try to calculate what performance would be required / expected), and then to follow that up with experiments to validate (or correct) and refine our initial estimate. The advantage of this approach is that the estimate helps us to design the experimental parameters and gain an understanding of what the important variables are, while the experiment validates and refines our understanding. Either experiment or analysis alone is often insufficient to gain a good working knowledge of the problem at hand.

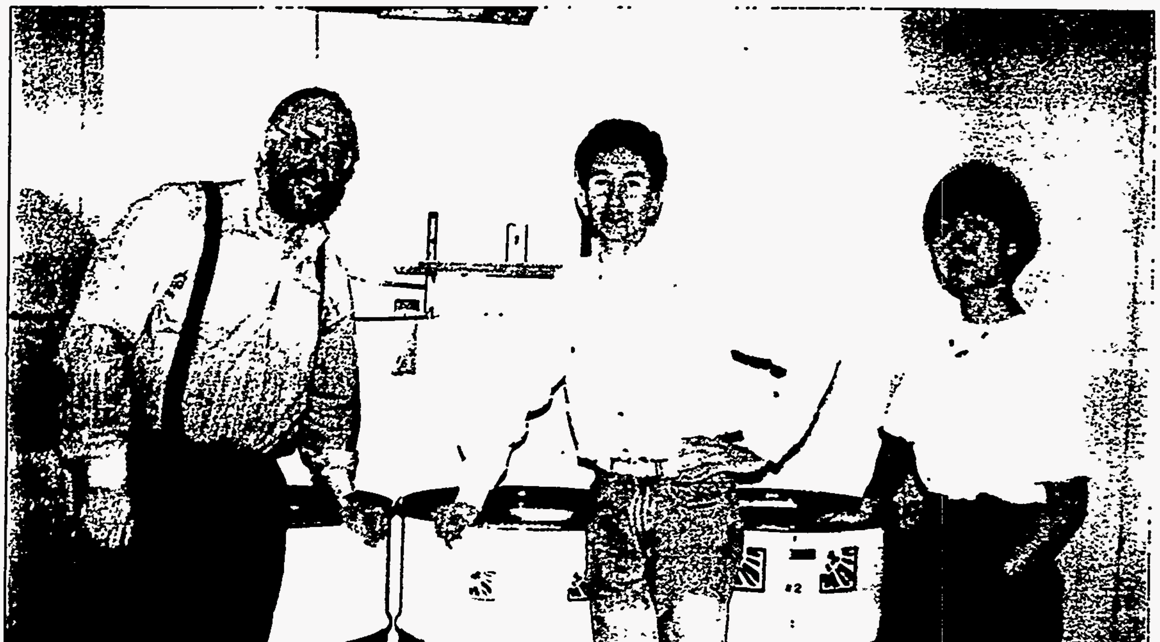


Figure 1.1: Team KSI

Guy Immega, President — Dr. Jeremy Wilson, Engineering Manager — Ms. Gloria Chow, Software Engineer

2. System Design Considerations

In this section we present the results of calculations of several critical system design parameters that are a direct result of the nature of the drum inspection problem (as detailed earlier in section 1.1).

2.1. Viewing Geometry

2.1.1 The Pin-Hole Camera Model

Much of the analytical work is based on geometry and trigonometry. One important ratio to know about is the displacement/range ratio that describes how the image of a point is projected onto the image plane for a pin-hole camera:

The pin-hole camera model leads to the following simple relationship between the location of a point and its image on the sensor:

$$s / f = x / z$$

where

s	=	sensor plane position,
f	=	focal length,
x	=	the point's position perpendicular to the optic axis, and
z	=	the point's position along the optic axis.

Since what we measure in the image is in terms of pixels, rather than a direct measure of position on the sensor plane, a simple refinement to the above that is more convenient is:

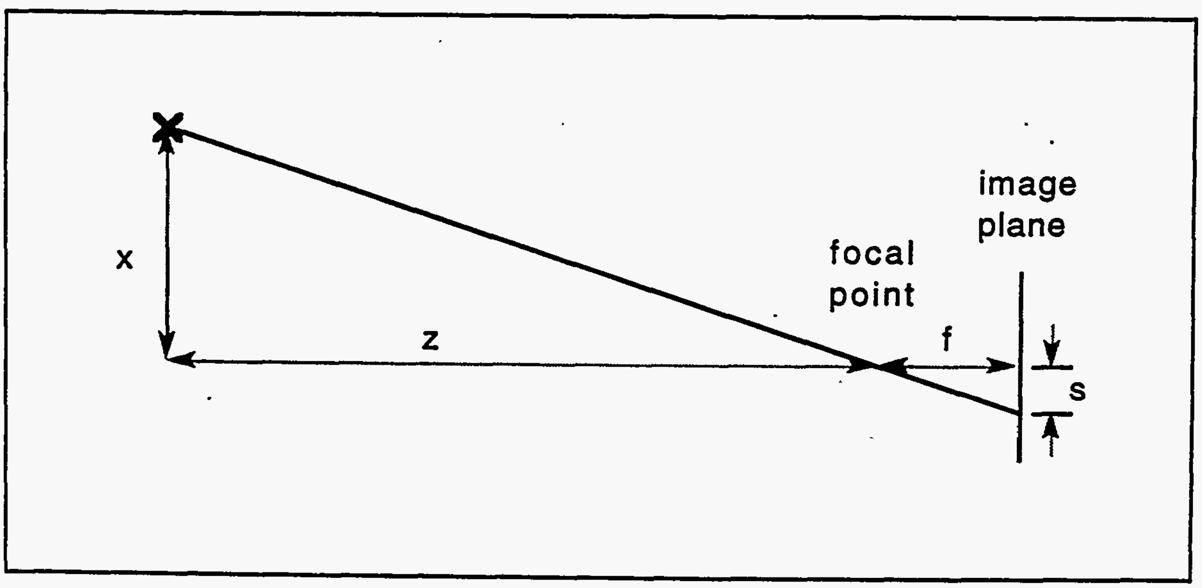


Figure 2.1: The Pin-Hole Camera Model

$i \cdot e / f = x / z$

where

i = the points location on the image plane measured in pixels from the center,

e = the size of a pixel on the sensor (typically about 10 μm).

2.1.2 Lens, camera, and drum stand-off distance.

The problem specification requires that we be able to see the entire drum in a single image, and operate the camera within a 30" aisle.

From the above relationship it is easy to determine how far away a given camera (specified in terms of the size of its imaging array) will need to be from the drum as a function of the focal length of the lens. We refer to this distance between the front edge of the drum and the focal point of the camera as the **stand-off distance**. The equation for stand-off distance can be easily derived from the pin-hole camera model as:

$sd = dh * f / sw$

where:

sd = stand-off distance,

dh = drum height (34" for a 55 US gallon drum + 1.5" margin top & bottom), and

sw = sensor width, and

f = focal length.

From this relationship we can note that the stand-off distance is reduced if the sensor width is

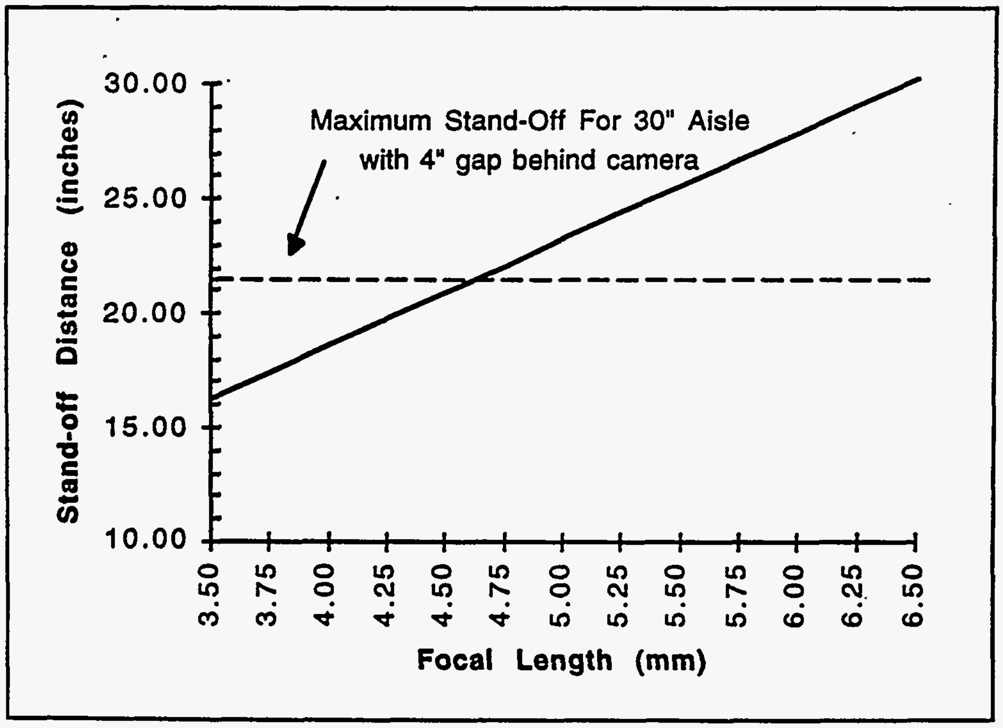


Figure 2.2: Relationship between stand-off distance and lens focal length

increased, or equivalently, for a given stand-off distance a longer focal length lens can be used. A related observation is that the camera should view the drum in a "portrait" orientation, i.e. with the longest dimension of the sensor array aligned with the longest dimension of the drum. On this basis we selected a color 3-CCD camera with a standard 1/2" C-mount that had a larger than normal sensor area: the **Hitachi HV-C20**. This camera has a sensor size of 7.95 mm x 6.45 mm (versus the 6.4 mm x 4.8 mm for a standard 1/2" C-mount camera), and a separate CCD for red, green, and blue leading to the best possible resolution (single CCD color cameras have poorer resolution because a checkerboard pattern of filters is overlaid on the array to extract red, green and blue). Figure 2.2 illustrates the relationship between stand-off distance and lens focal length for this Hitachi camera.

The body of the Hitachi HV-C20 camera is 4.5" (11.5 cm) long. Allowing a further 4" (10 cm) gap behind the camera to allow for its power & video cables, as well as allowing for a drum that is displaced slightly into the aisle, implies that the camera's focal point can be no more than 21.5" (54.6 cm) from the drum.

The calculations imply that a lens with a focal length close to 4.6 mm would be the best choice. Unfortunately the selection of focal lengths commercially available in the range 4-5 mm is quite limited. For our experiments we selected a Cosmicar Pentax 4.2 mm C-mount lens (part. no. C60402), with a manual iris and fixed focus. We also experimented briefly with a higher quality Century Precision 5.7 mm lens to compare the level of radial distortion.

2.1.3 Radial Distortion and Automatic Calibration

As can be seen from Figure 2.2, the narrow aisle results in the requirement for a very wide angle lens. A problem with many common wide angle lenses is appropriately known as "barrel distortion" (also known as **radial distortion**). A square centered on the imaging array becomes bent outward like an old style wine barrel.

Figure 2.3a shows the severity of the radial distortion for the 4.2 mm lens. The white squares show where the label borders would be if there were no distortion. In comparison, the image in Figure 2.3b taken with a high quality 5.7 mm lens is much less distorted. The level of distortion in Figure 2.3a poses a serious problem for the vision system because the calculation of the drum label's position and orientation with respect to the camera is based solely on the location in the image of critical points on the label (the interior corners of the square border). The locations of these points are significantly altered by the distorting lens.

Fortunately, KSI was already aware of the radial distortion problem for wide angle lenses, and had developed a functional (alpha) version of a program that automatically calibrates the combination of lens, camera, and frame grabber. One of the results of the calibration is an estimate of the radial distortion. The software did require some further work to enable it to cope with such a severely distorted image, and will require further improvements to ensure that convergence to a sensible result is more reliable (several runs of the calibration software were sometimes required before the program converged successfully on the parameters for the distorting lens).

Figure 2.4 illustrates the special calibration target that is placed in front of the camera (refer to photograph sheet). It is a prism shaped object with two 8" x 8" faces patterned with a regular array of black squares. The exterior angle between the faces is 120°. A file is created that accurately defines the 3D position (measured manually) of each of the corners of the black squares on the target with respect to an origin on the target.

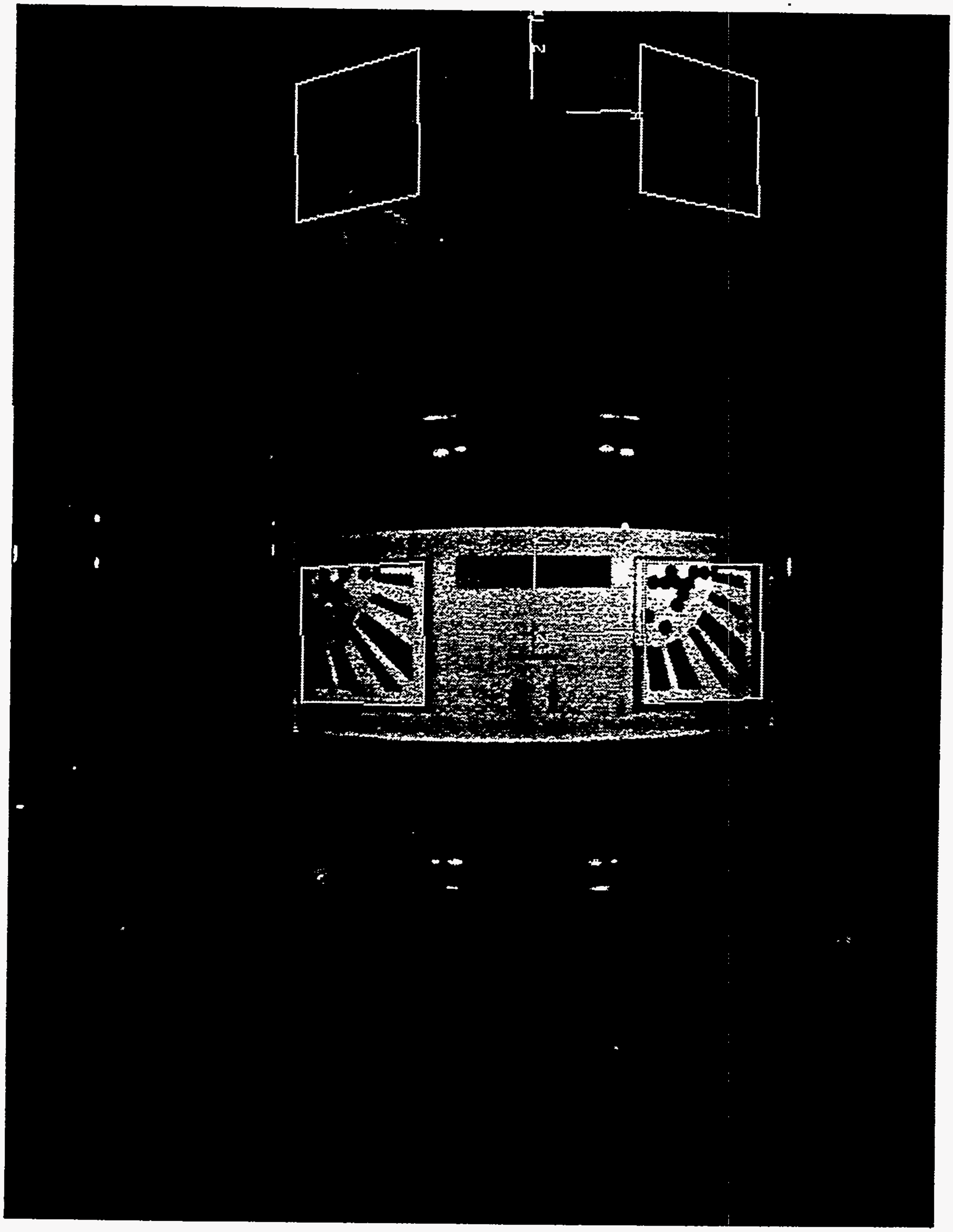


Figure 2.3a: Barrel Distortion and Eagle Eye correction
(Medium quality 4.2 mm lens;
4" squares on labels)

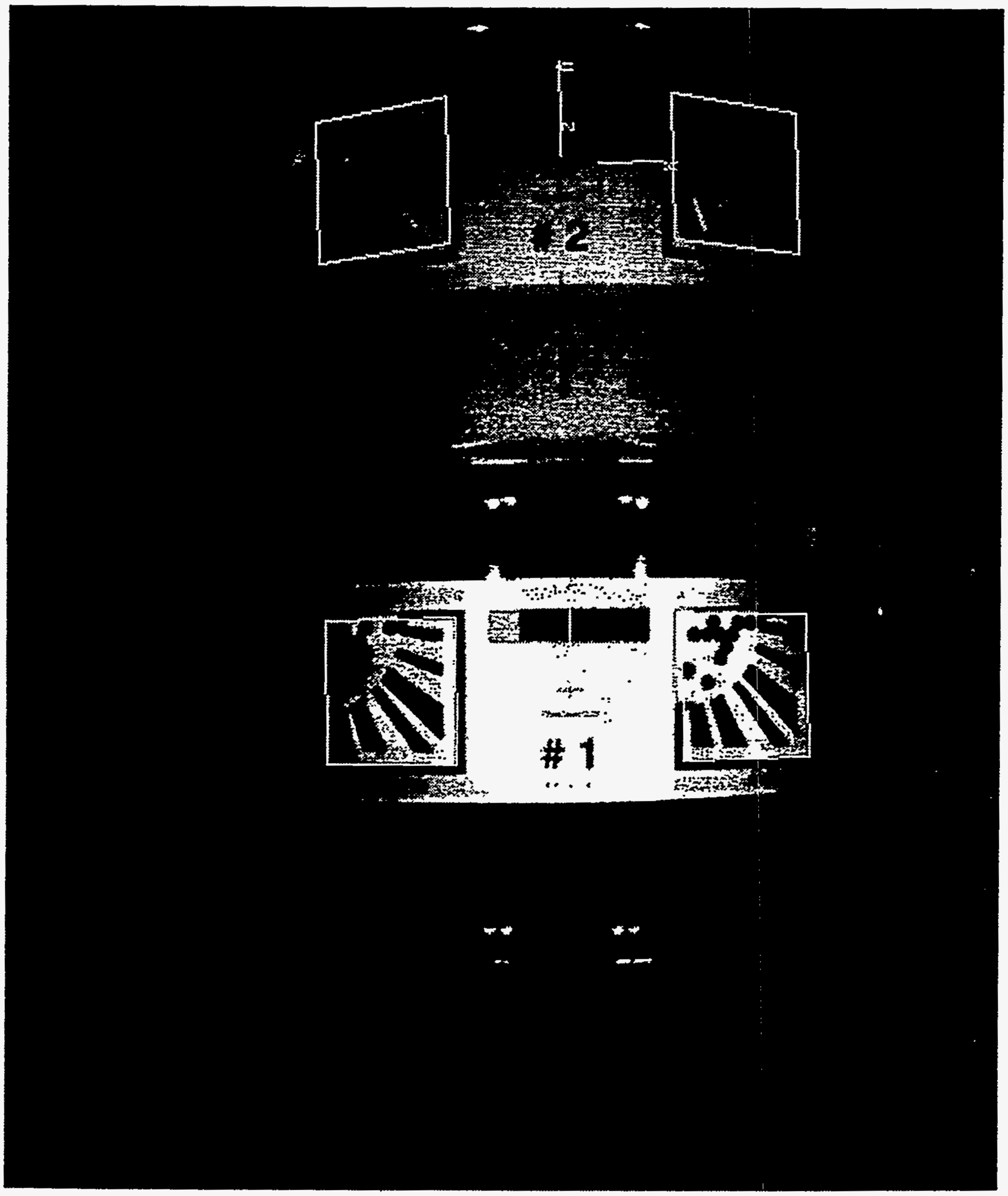


Figure 2.3b: Barrel Distortion and Eagle Eye correction (High Quality 5.7 mm lens; 4 " squares on labels)

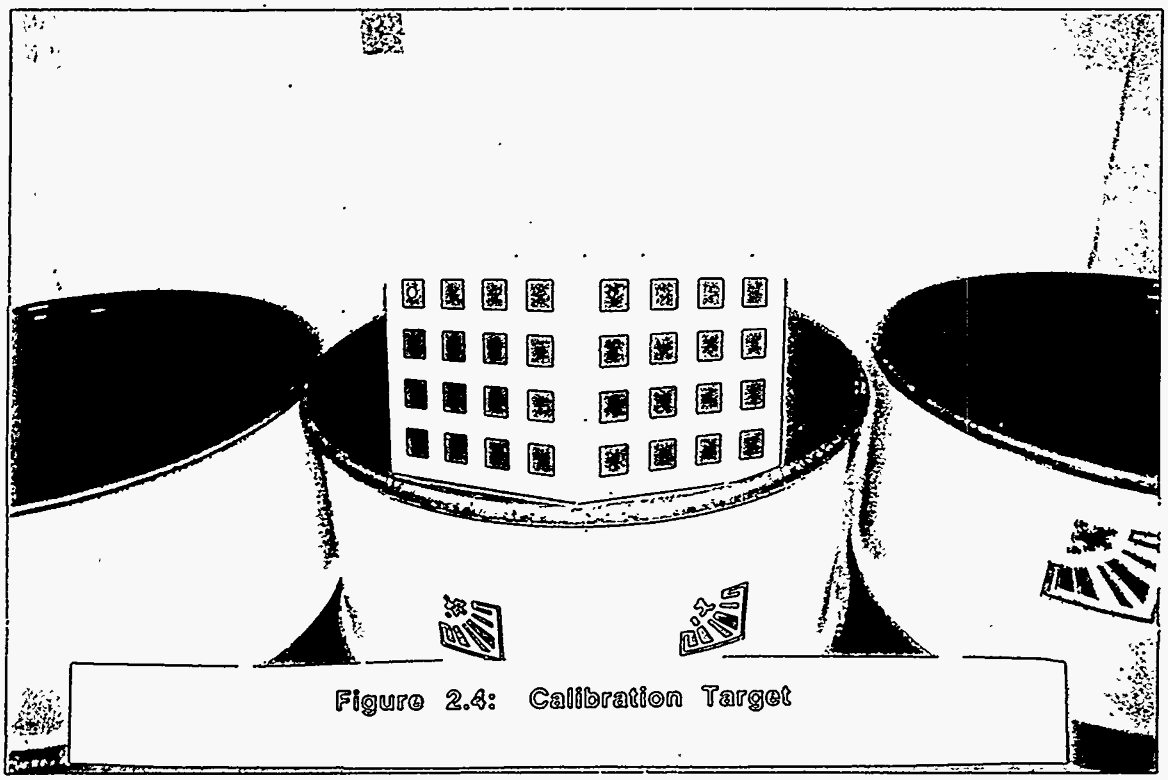


Figure 2.4: Calibration Target

A single image of the calibration target is acquired and the known characteristics of the camera are entered by the user from the manufacturers specifications for the camera (specifically, the no. of sensor elements horizontally and vertically and the sensor element size). The program automatically finds the corners of the black squares in the image and then iterates to find a set of parameters that accurately map the known 3D positions of the calibration target to the locations at which they were found on the image plane, a process which typically takes about 15-30 minutes of computing time on a Quadra class Macintosh. The result of the calculations include the position and orientation of the target, the focal length and radial distortion coefficient for the lens, an aspect ratio correction factor, and the location of the image center.

The extent of the distortion for the Cosmicar-Pentax 4.2 mm lens used in the experiments is illustrated in Figure 2.5, and compared with the distortion of two other lenses: a high quality Century Precision 5.7 mm lens, and a medium quality Cosmicar-Pentax 8.5 mm lens. As can be seen, a high quality lens has significantly lower radial distortion than a medium quality lens with the same focal length. The distortion follows a cubic relationship with the result that the distortion is small at the center of the image, but becomes very pronounced in the image periphery.

The lens and camera parameters determined by the automatic calibration are fed into the Eagle Eye software, which is then able to correct for the true image center and for the radial distortion. The result is that the position and orientation calculations remain surprisingly accurate despite the distortion. Figures 2.3a and 2.3b show this correction. Drawn over the image is the location of the faces following correction by Eagle Eye. By holding the page almost flat and sighting along

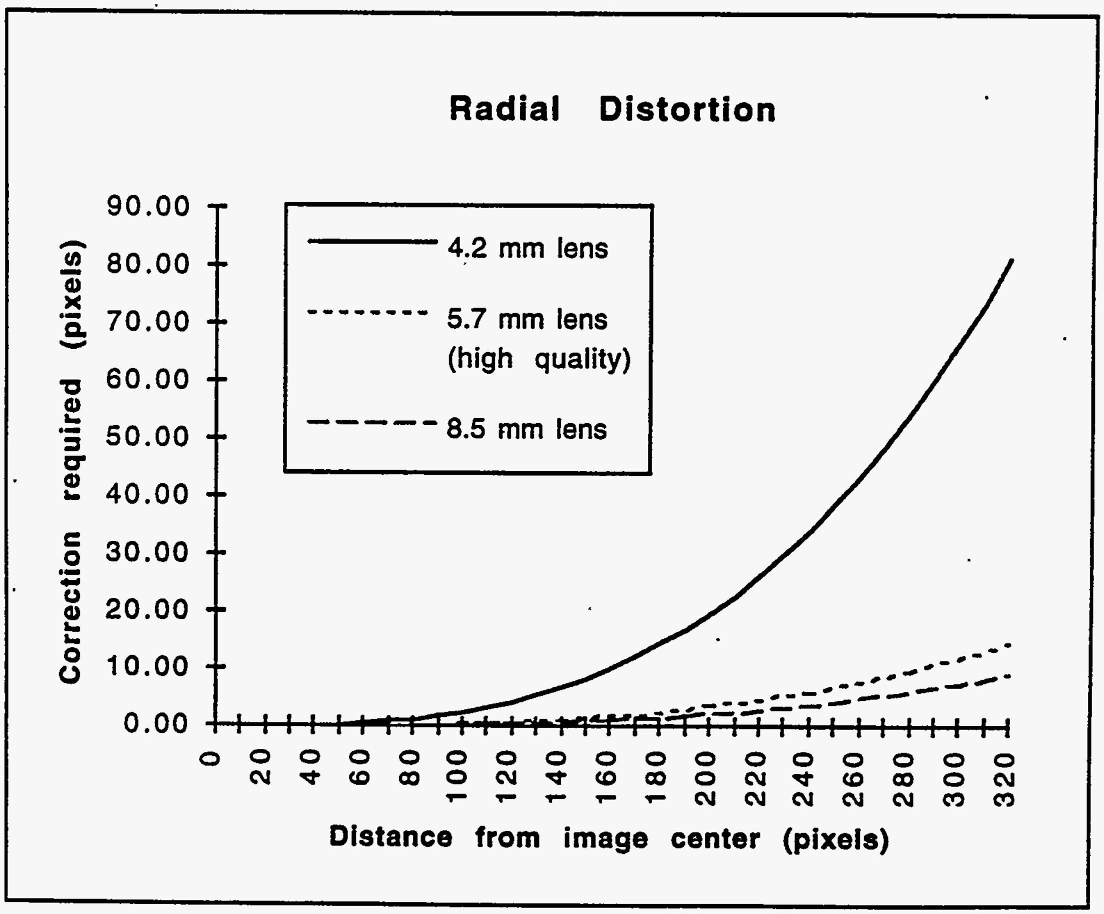


Figure 2.5: Distortion Correction for Three Lenses

the lines that form the vertical edges of the squares you can see that Eagle Eye has successfully corrected these lines back to a position in which the lines of the upper and lower labels are co-linear, as they would have appeared if viewed through a truly planar (i.e. non-distorting) lens.

At the time of writing this report we have no alternative way to measure the calibration parameters to assess the accuracy of the calibration process itself. However we were able to estimate the accuracy by two means: performing multiple runs of the calibration with different optimization criteria, and performing multiple runs of the calibration with slightly perturbed dimensions for the model of the calibration target. These results indicated that the focal length and radial distortion values should be in error by no more than 2%. Since repeatability of camera positioning is of greatest importance, not absolute accuracy, this level of error in the lens calibration is not a problem while operating with one lens. However if the lens has to be swapped-out, and the replacement lens does not have very similar characteristics, the baseline images would need to be recaptured or warped to fit the characteristics of the new lens (so that change detection via image subtraction remains valid). This suggests that it is important that the calibration parameters be recorded in association with a set of baseline images in case such processing needs to be performed.

2.2. Adhesive Drum Label

This section discusses the design of the adhesive drum labels. The Eagle Eye vision system uses the special pattern printed on this label to uniquely identify a drum and to determine its position and orientation with respect to the camera.

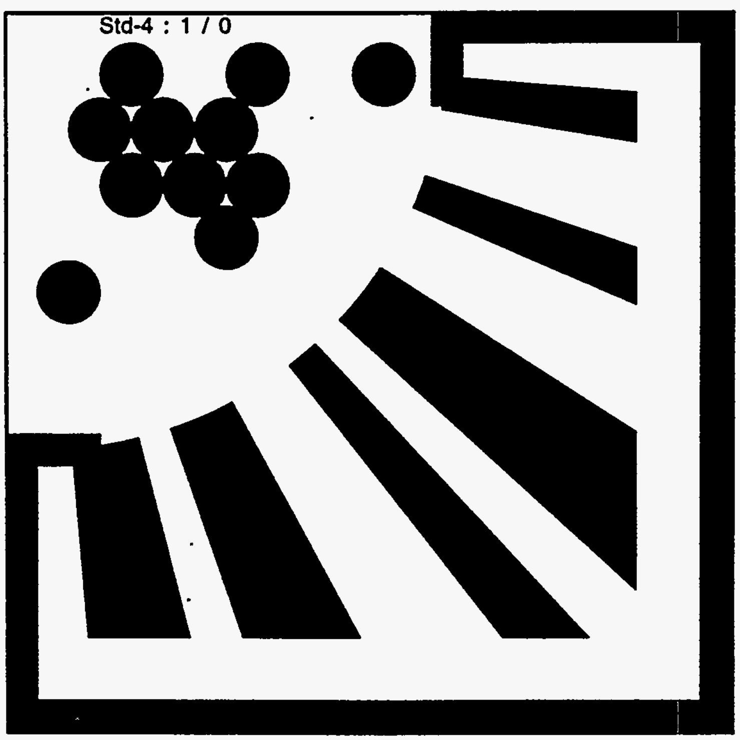


Figure 2.6: Example of one face of an Eagle Eye marker.

2.2.1. Face Pattern

KSI's Eagle Eye marker tracking system uses a proprietary pattern on each face of a multi-faceted marker. This new face pattern was developed subsequent to the face pattern shown in the original BCD proposal (under work partially funded by the Canadian Space Agency), and enables an improvement in the speed of tracking, the amount of information encoded on the face, and error correction of this information. Figure 2.6 is an example of this pattern. The radial segments are the same on any face, and are the means by which Eagle Eye rapidly distinguishes the face of a marker from other objects in the image. The border pattern is what Eagle Eye uses to accurately determine the position and orientation of the marker. The pattern of black dots encodes 31 bits of information that tells Eagle Eye which type of marker it is seeing, what the unique identity of the marker is, and which face of that marker has been seen. Eagle Eye markers can have any number of faces of any size, with at least two non-coplanar faces needed in order to obtain accurate position and pose information. For each type of marker, a data file defines an accurate model of its physical dimensions.

2.2.2. Encoding Scheme And Error Correction

The new face design supports a more structured data scheme than the simple face numbering used previously. The standard pattern encodes 16 bits of data. One bit is reserved as a special flag bit which indicates whether the marker is a standard KSI marker or a user defined marker. The remainder of the bits are divided into three variable width fields: a field that defines which type of marker the face is attached to, a field that specifies the marker's i.d. number, and a field specifying which face of the marker this is. For a user defined marker, the marker type field can be omitted if only one type of marker is needed (as is likely to be the case for the drum labels). If each label has two faces then only one bit in the face field is required to distinguish between the left and right faces. This leaves 14 bits for the i.d. field, which allows us to distinguish 16,384 unique drum labels (a typical warehouse is expected to have approx. 7,000 drums).

The number of dots on the marker is actually 31. The 15 dots not used to encode drum face identity are used to represent a type of checksum. A decoding algorithm uses this information to correct for up to 3 errors in any of the 31 bits. This makes the data reading process quite robust and would allow, for example, a 1/4" spot to mar the label and still enable it to be correctly read.

We have also made provision for a 21 bit data / 10 bit checksum version of the marker which could allow for 524,288 two-face labels (which may be enough to allow all drums in DOE warehouses to be uniquely labeled).

(NOTE: the Eagle Eye marker pattern is subject to non-disclosure due to potential patent application.)

2.2.3. Label Position On Drum

In order for the camera (with a wide angle lens) to view all of one side of a drum, the camera must be aimed roughly at the center of the drum. Therefore, the best position for the drum label is in the center of the drum (as shown in Figure 2.3a). This is because the vision system assumes that the faces are flat. In the middle position the effect of drum curvature on the face is minimized (from the camera's viewpoint). However we recognize that for various reasons (e.g. existing annotation on a drum that cannot be obscured) it may occasionally be necessary to mount a label in the top or bottom region of the drum. Therefore we included in our experiments a label mounted near the top of the drum to investigate the effect on camera positioning accuracy. The results of these experiments are reported in Section 5.

2.2.4. Size, Separation, Number Of Faces

Once the camera, lens, and stand-off position have been chosen, the dimensions of the adhesive label can be determined. Specifically, we need to determine the size of each marker face, the separation of the faces, and the number of faces.

Figure 2.8 illustrates the nature of the geometry for viewing a label in the middle of the drum. Appendix A1 presents the detailed calculations involved in estimating the minimum size for the label. We want the label to be as small as possible to minimize the surface area of the drum that is obscured. Figure 2.7 summarizes these results.

The Eagle Eye face patterns on either side of the label cannot be smaller than 2.5" square without compromising the ability of Eagle Eye to reliably detect the face patterns. The face width and height cannot be more than about twice the size shown (i.e. not more than about 5") without inducing an unacceptable amount of curvature in the top and bottom lines of the face, especially for an off-center label. As will be shown later in Section 5, this small size was adequate for a label placed in the center of the drum (although with marginal performance in the tilt axis); however, it was found to be too small to achieve reliable operation for a label placed near the top of the drum. Further experiments indicated that a size of 3.2 inches was a good choice for a label with improved performance on the tilt (up-down) axis of camera positioning, but we did experience problems with getting Eagle Eye to reliably read a label placed near the top of the drum due to the curvature.

There are several options as to the number of face patterns to have on the label. As noted earlier, at least two faces are needed to achieve good range and orientation accuracy. However Eagle Eye allows markers to have any number of faces (information encoded in the dot pattern enables Eagle Eye to distinguish between each face). For example, a label with three faces (with the same spacing as indicated in Figure 2.7 below) would allow the label to be viewed over a wider range of angles. Eight faces equally spaced on a label that wrapped around the full circumference of the drum would allow a drum to be recognized at any arbitrary rotation and so the drum could be placed on the palette without concern for the label's position. A disadvantage of such a label is that it is likely to be more difficult to apply to the drum. Since the objective of Phase 1 is to establish the technical feasibility of Automatic Baseline Change Detection, operational issues such as drum placement are not the main focus. Therefore the two face label seems a good choice for Phase 1.

Figure 2.7: Minimum Label Size

Face width and height	6.39 cm	2.52 inches
Face separation (between inside edges)	16.30 cm	6.42 inches
Total Label Width	29.08 cm	11.45 inches
Label Area	185.8 cm^2	28.8 in^2

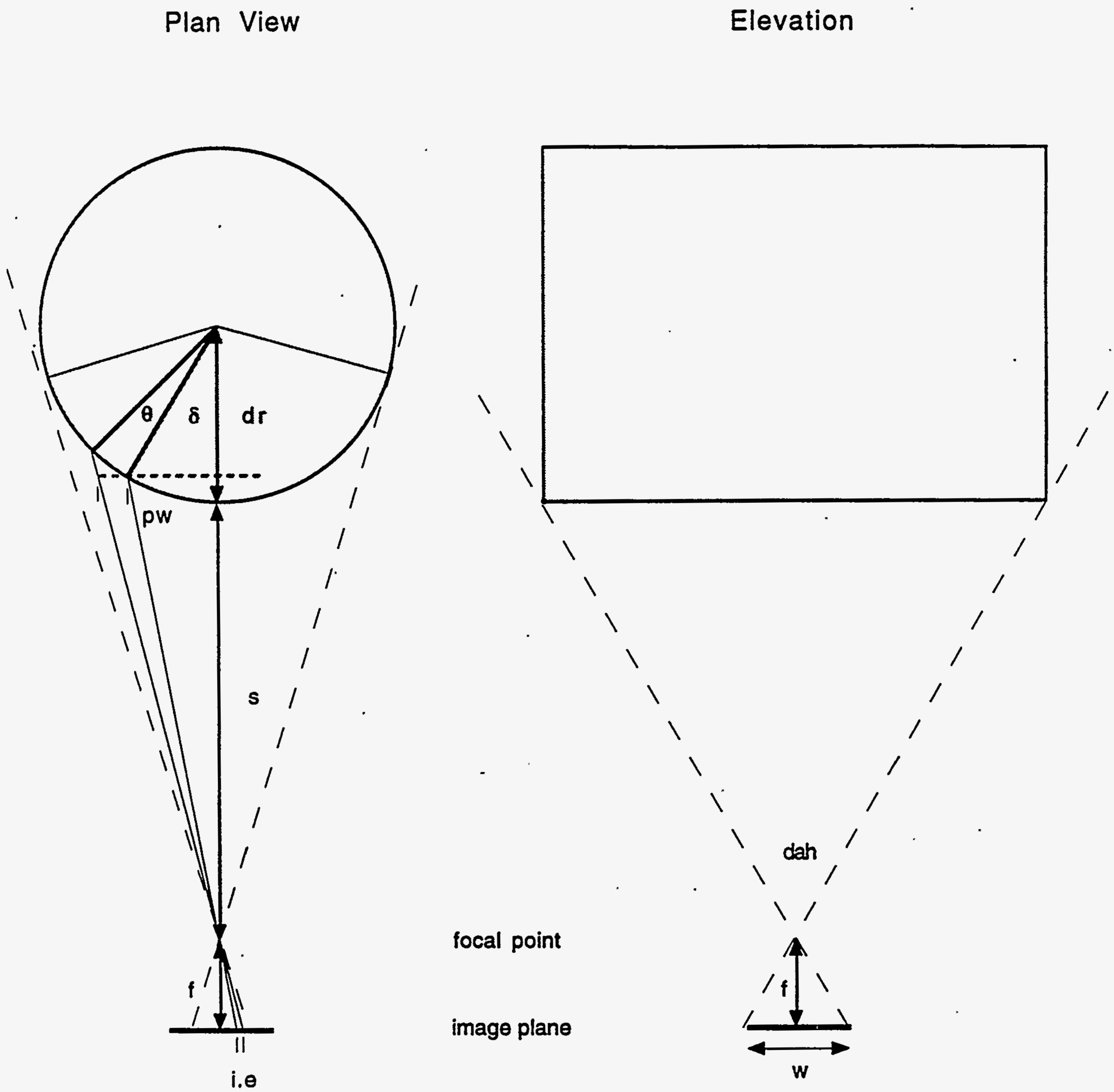


Figure 2.8: Drum Label Viewing Geometry

3. Experimental Set-Up

3.1. Camera, Lens, and Frame Grabber

At the time of the experiments we had not yet obtained the Hitachi HV-C20 color 3-CCD camera because Hitachi had only just put the camera on the market. In its place, we used a Pulnix TM-7CN black-and-white CCD camera with a standard 1/2" C-mount and standard size array (6.4 mm x 4.8 mm for the Pulnix, versus 7.95 mm x 6.45 mm for the Hitachi camera) with the same number of CCD elements as the color camera. We adjusted the stand-off distance for the experiments from 18.2" (calculated for the Hitachi camera) to 22.5" to account for the smaller size of the array (i.e. smaller field of view). This change has negligible effect on the results of the repeatability experiments, and simply ensured that we could see the entire drum in a single image.

As noted in Section 2.1.2, a Cosmicar Pentax 4.2 mm C-mount lens with a manual iris and fixed focus was selected as the lens for the experiments. A lens with such a short focal length has large depth of field when the iris is stopped down. However the focus is very sensitive. To adjust the focus to be as sharp as possible for a typical aperture setting and for a drum distance of around 22.5" we modified the "back focal distance" adjustment for the Pulnix camera (which is achieved by loosening several small locking screws and unscrewing the C-mount collar to achieve the best focus). This adjustment is exactly equivalent to a normal focusing mechanism, and had the advantage that we could lock the lens on a fixed focus setting.

While we achieved surprisingly good results from this lens (thanks to the radial distortion correction discussed earlier in Section 2.1), we recognized that this lens was pushing the limits of the automatic calibration, was reducing the resolution in the periphery, and had poorer focus than we would like to see (esp. in the image periphery). Consequently we did some preliminary investigations of an alternate lens of higher quality: a Century Precision 5.7 mm lens. As shown earlier in Figure 2.5, a high quality lens has a much lower radial distortion than a cheaper lens, but the higher quality lenses can be as much as 10 times as expensive.

The frame grabber used to acquire images from the camera was an IMAXX M1 black-and-white frame grabber (a Macintosh NuBus card), produced by Precision Digital (WA). This frame grabber has several advantages: it is highly configurable allowing fine control of sampling rate and image clipping; it uses a proprietary technique for achieving high image stability; and it is available for a wide range of camera types (a version capable of acquiring color images is being purchased for phase 1B).

For each experimental round we ran the automatic calibration to determine the parameters of the lens / camera / frame grabber system. An example result of this calibration process is shown below in Figure 3.7.

3.2. Test Room

In order to be able to completely control illumination, we choose to set up the experiments an unused cool storage room. With the door of this room closed we could eliminate any extraneous sources of light. Figure 3.1 (photograph) shows the overall setup of this test room.

3.2.1. Optical Bench

To achieve accurate manual adjustment and measurement of camera position, an "optical bench" was set up as shown in Figure 3.2 (photograph).

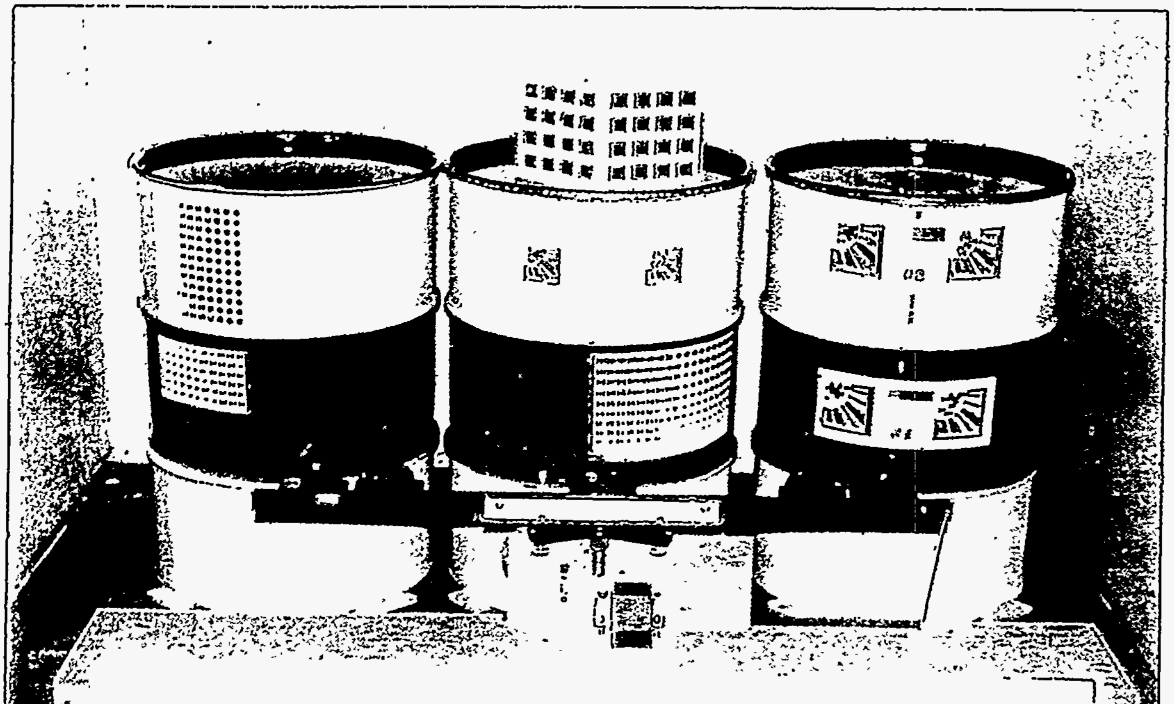


Figure 3.1: Overview of Test Set-up

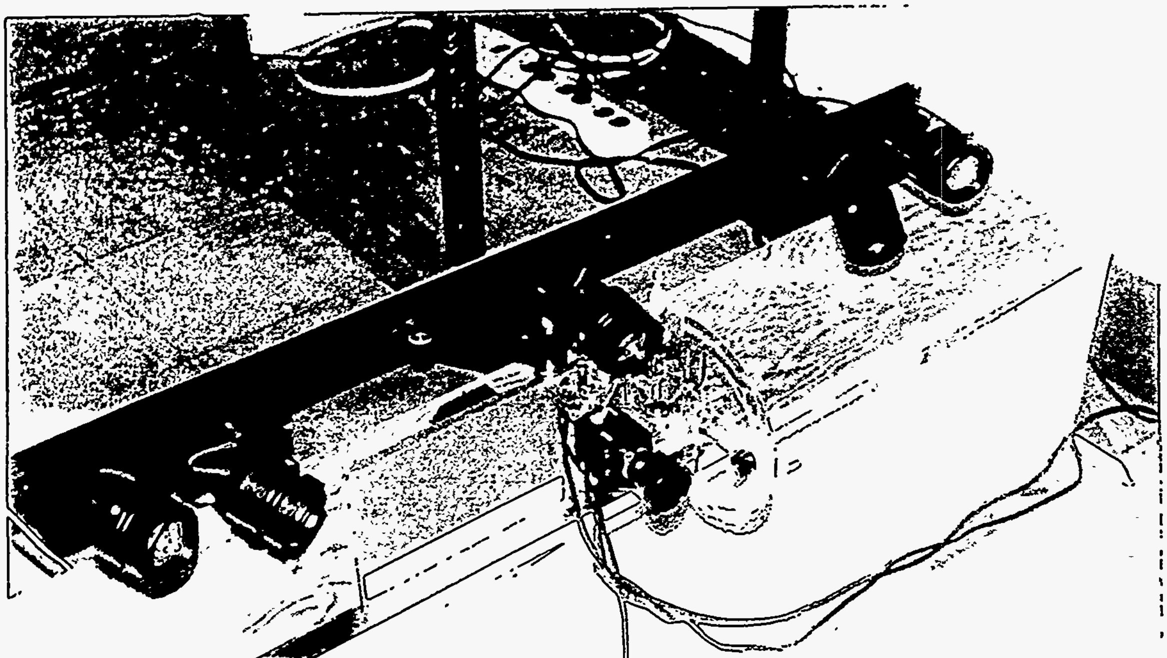


Figure 3.2: Optical Bench and Track Lighting

Figure 3.7: Example Calibration Result (for Cosmicar Pentax 4.2 mm lens)

Input Parameters	**Value**
No. of CCD elements (from manufacturer's spec.)	768 x 480 (horizontal x vertical)
Image Size (determined by frame grabber settings)	640 x 480 (horizontal x vertical)
Size of CCD elements (from manufacturer's spec.)	8.4μm x 9.8 μm

Output Parameter (computed by calibration program)	**Value**
Focal Length	4.335 mm
Aspect Ratio Correction Factor	1.030
Radial Distortion	0.0239 mm^{-2}
Image Center	320.5, 265.2 (horizontal, vertical)

Figure 3.3 (photograph) is closer view of the camera assembly, which is mounted securely on a heavy metal plate that can be slid along the bench (referred to as the Y axis because the camera is mounted at 90°) parallel to a finely graduated ruler.

The camera is mounted on the tilt axis with an associated protractor for measuring the tilt angle. The axis of tilt was carefully aligned with the focal plane of the camera so that tilting the camera would not induce changes in other axes. The tilt mechanism it attached to a vertical slider with 2" of travel. The slider's position can be firmly locked in place with the lever that appears directly above the camera body in figure 3.4. A micrometer allows fine position measurement (to 5 thousandth of an inch) over a 1" range, while a printed scale allows for measurements of the full 2" range of the slider. This vertical direction is referred to as the X axis.

Movement in the Z direction (towards or away from the barrel) is achieved by moving the whole bench. Figure 3.5 shows the guide plates and associated measurement scale, allowing for 7" of travel. The scale was carefully positioned to reflect the distance from the front of the drum to the focal plane of the camera.

3.2.2. Illumination

For ambient illumination, the fluorescent lights in the test room could be switched on or off. For stronger illumination that moved with the camera, a set of track lights were mounted directly above the camera on a shaft attached to the metal plate (see Figure 3.2). Five quartz-halogen spot lights, each of 50W provided ample lighting, and could be individually adjusted so that the overall illumination was even. A standard light dimmer was used to control the brightness of the lights, and a digital voltmeter enabled us to control the power output of the lamps with good repeatability.

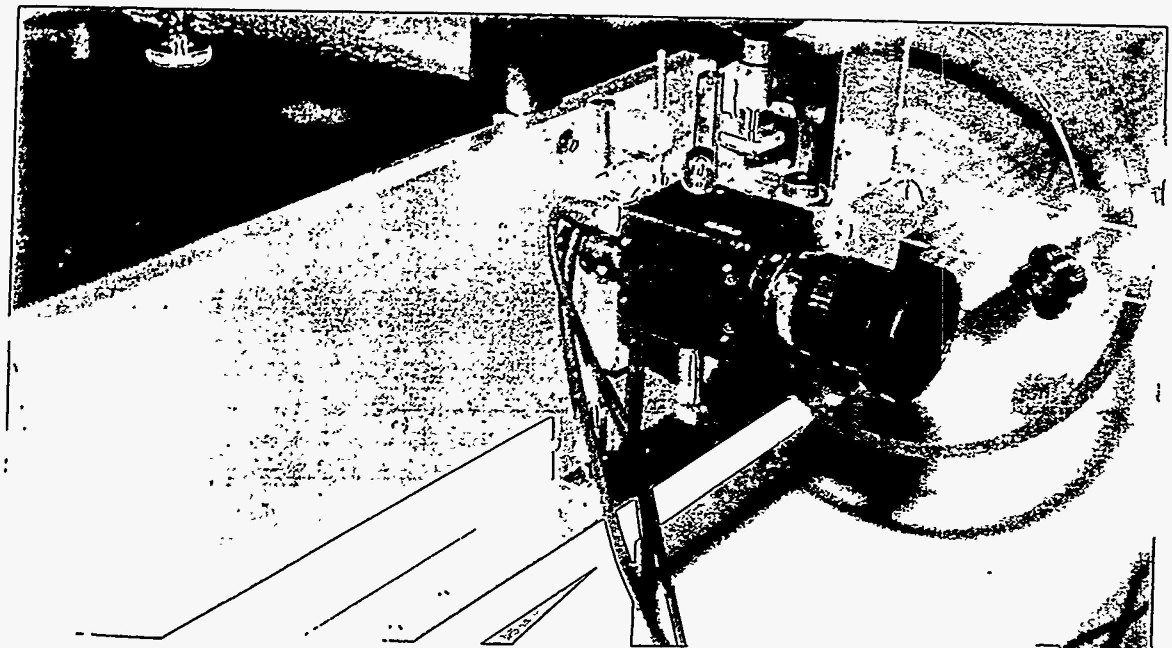


Figure 3.3: Optical Bench X-axis measurement

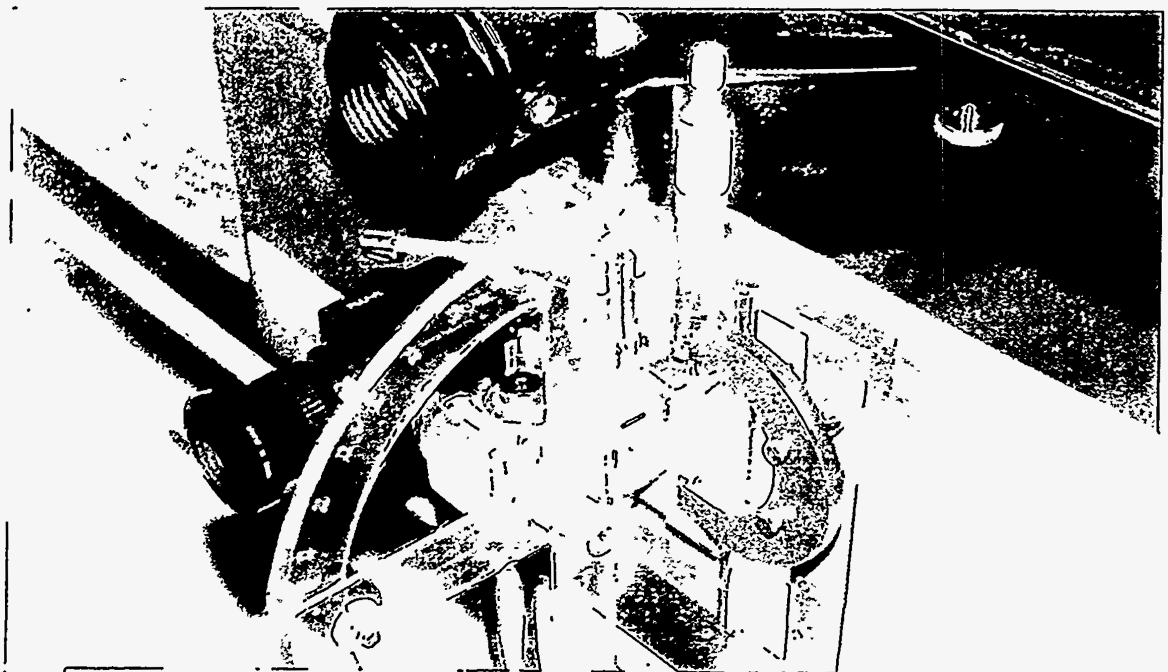


Figure 3.4: Optical Bench close-up (tilt and Y-axis)

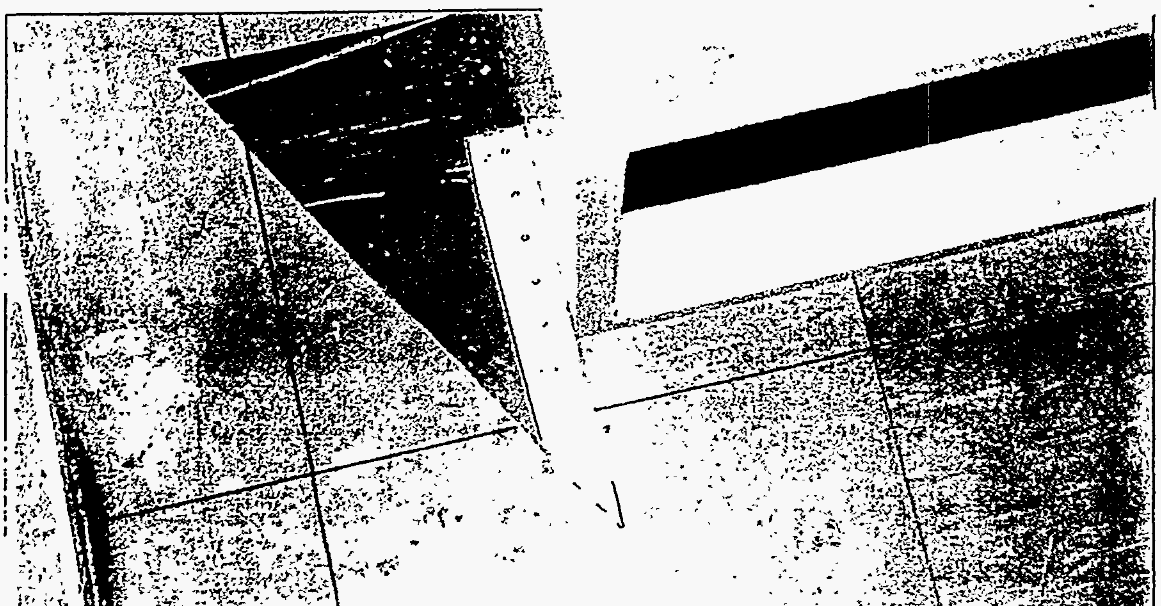


Figure 3.5: Optical Bench Z-axis measurement

3.2.3. Drums

Three new, empty, 55 US Gallon drums were set up as shown in Figure 3.1. The drums were held in fixed positions by blocks on the floor, as shown in Figure 3.6. As can be seen in this photograph, accurate rotational positioning of the drums was achieved using a printed scale affixed to the base of the drum with the reference mark on one of the holding blocks.

3.2.4. Labels

The face patterns for each label were printed by a program called "FaceMaker" that KSI developed as a partner application to Eagle Eye. This program allows the marker type, marker i.d. number, and face i.d. to be entered in a simple dialogue and the face then printed on a laser printer. An accurate label guide sheet was prepared using a drawing program, and the faces carefully affixed to this guide sheet using rubber cement (in the future, the FaceMaker application will be extended to allow the entire label to be printed at once, however this work was not within the scope of the Phase 1A tasks). The labels were aligned with registration marks on the drums, and attached with removable tape.

3.2.5. Dot Patterns For Change Detection Tests

For the illumination and change detection experiments, two types of dot pattern were created in a drawing program. One pattern was set up with dots of varying size (Figure 3.8) and another pattern had 1/4" dots of varying contrast (Figure 3.9). Note that the contrast units (in %) are as defined by the drawing program, and are not the same as image gray levels. This issue is considered in more detail in Section 4.3.

These patterns were affixed to the drums both horizontally and vertically.

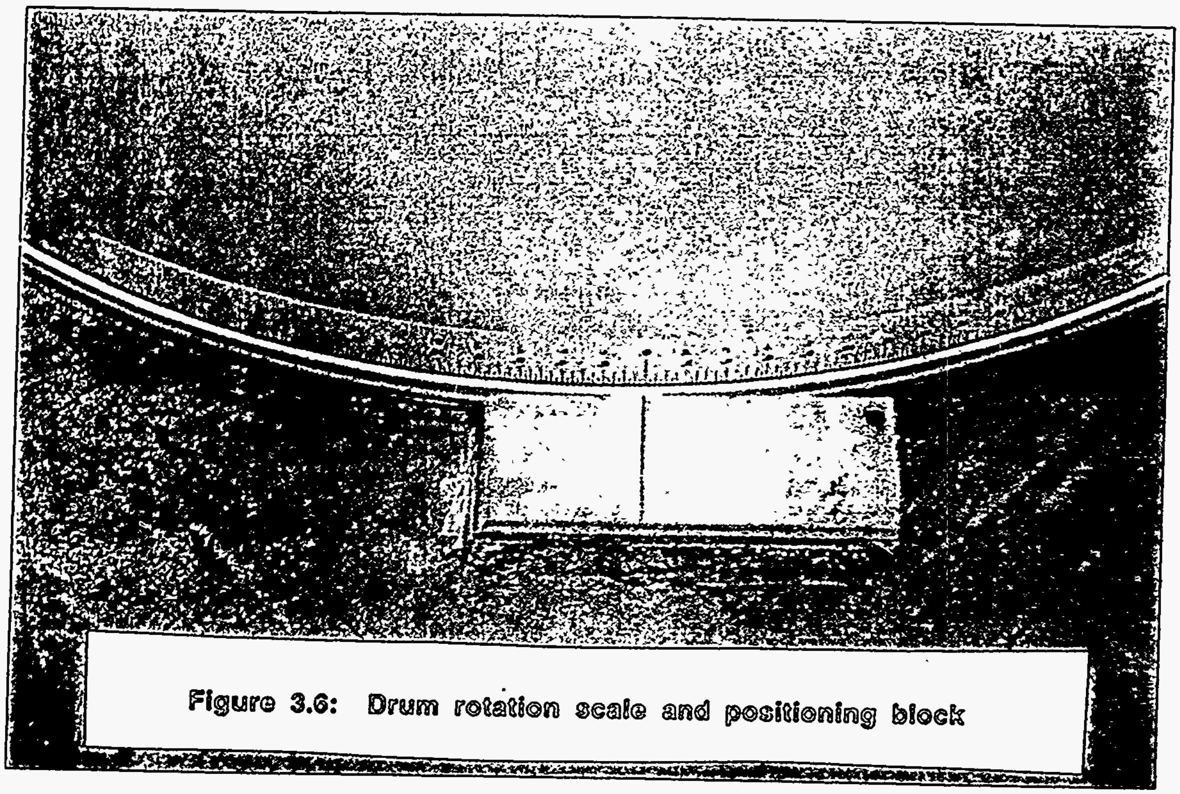


Figure 3.6: Drum rotation scale and positioning block

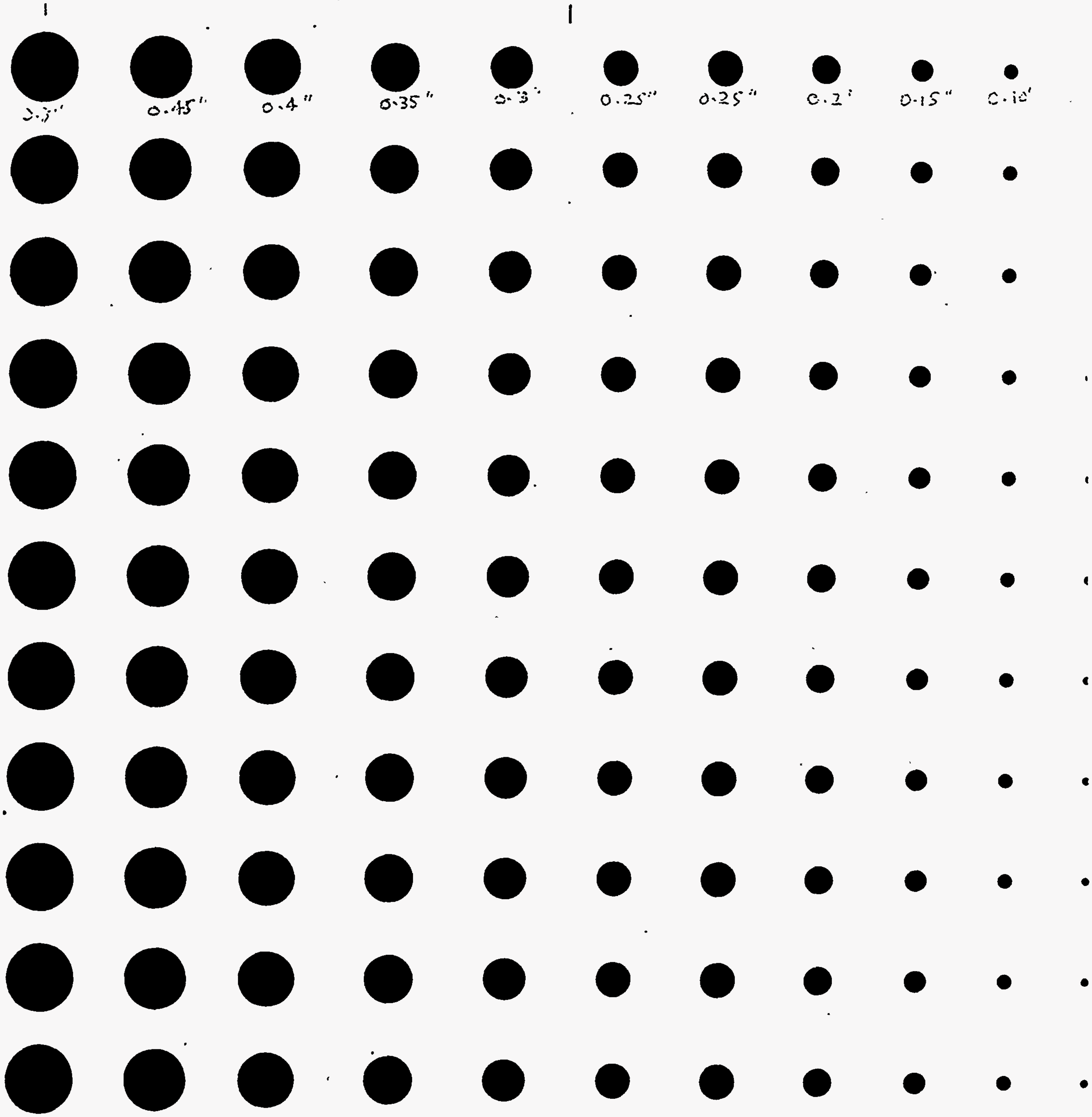


Figure 3.8: Variable Size Dot Test Pattern

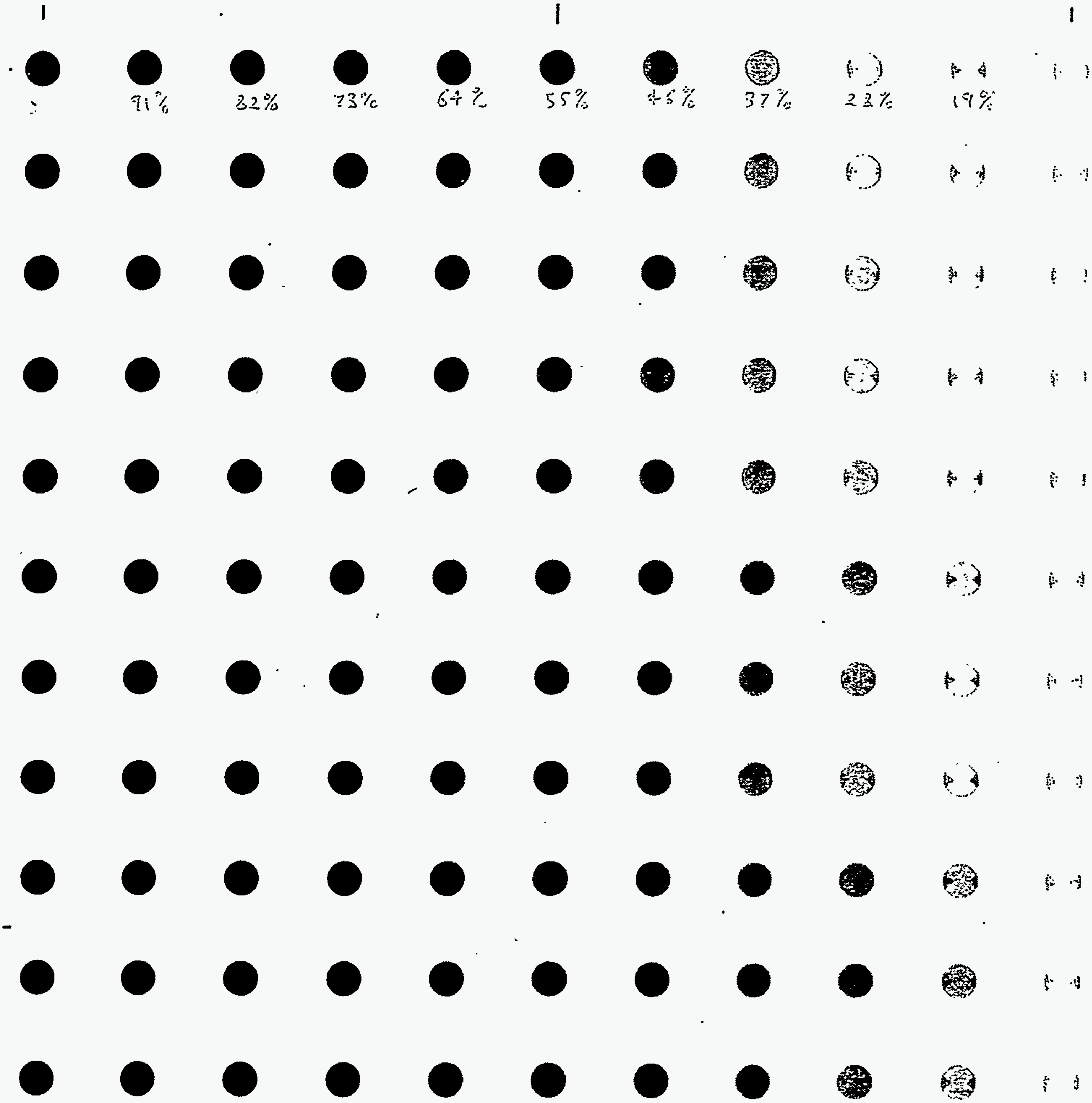


Figure 3.9: Variable Contrast Dot Pattern

4. Change Detection Experiments

The purpose of the Change Detection experiments was to determine the sensitivity of change detection to errors in position and orientation of the camera, the sensitivity to variation in illumination, and the effect of the curvature of the barrel on dot size and contrast.

Before describing the experiments in detail, we will review how automatic change detection works.

The major steps in automated change detection are illustrated by the data flow diagram in Figure 4.1. The *Baseline Image* is an image of the drum taken at the time the drum was certified by a human operator as being in good condition. The *New Image* is an image of the drum taken on a routine inspection of the drum by the mobile platform. This image must be taken from very nearly the same viewpoint as the Baseline Image to avoid introducing changes into the image that are due to seeing the drum from a different perspective rather than being due to any real change in the drum itself (how accurate this repositioning of the camera has to be is the topic of Section 4).

Seven main image processing steps are involved in determining if there has been any significant change in the drum:

1. **Image Registration:** Small errors in the repositioning of the camera can be dealt with by shifting the New Image with respect to the Baseline Image so that they are in more precise alignment. There are a variety of techniques for achieving this automatically and they come under the general heading of cross correlation. This processing step may not be necessary if we are able to achieve high enough repeatability in the camera positioning subsystem, but it was necessary in our experiments because we were intentionally introducing larger positioning 'errors' to determine the worst case error that could be allowed.
2. **Intensity Normalization:** Slight variations in the illumination conditions must also be dealt with before image subtraction can be meaningfully applied. Again, there are a variety of automatic techniques that can be used. One approach is to determine the intensity histogram (the number of pixels at each of the 255 discrete gray levels in the image) for both images, and then compute an intensity mapping function that adjusts the gray levels in the New Image so that they have the same distribution as in the Baseline Image. While we did not investigate Intensity Normalization techniques in task 1 (our illumination conditions were carefully controlled), we did investigate the sensitivity to illumination changes of the steps that follow it in the processing chain (see Section 4.3). We also explored a related technique called Ambient Subtraction (discussed in Section 4.4).
3. **Image Subtraction:** Corresponding pixels in each image are subtracted to create a new image of the same size. If the two images are exactly the same, the result will be an image of zero values. However there are always slight differences, and later in this section we discuss some of the sources of variation that should not be treated as significant change.
4. **Filtering:** There are various sources of image 'noise' (i.e. degradation of the image signal) that produce the kind of 'salt & pepper' variations in pixel values shown in Figure 4.3. Local area image operators such as median filtering or erode/dilate filtering can help to remove this image noise.
5. **Thresholding:** The purpose of the thresholding step is to select those pixels whose intensities indicate a potentially significant change in contrast between the two images.

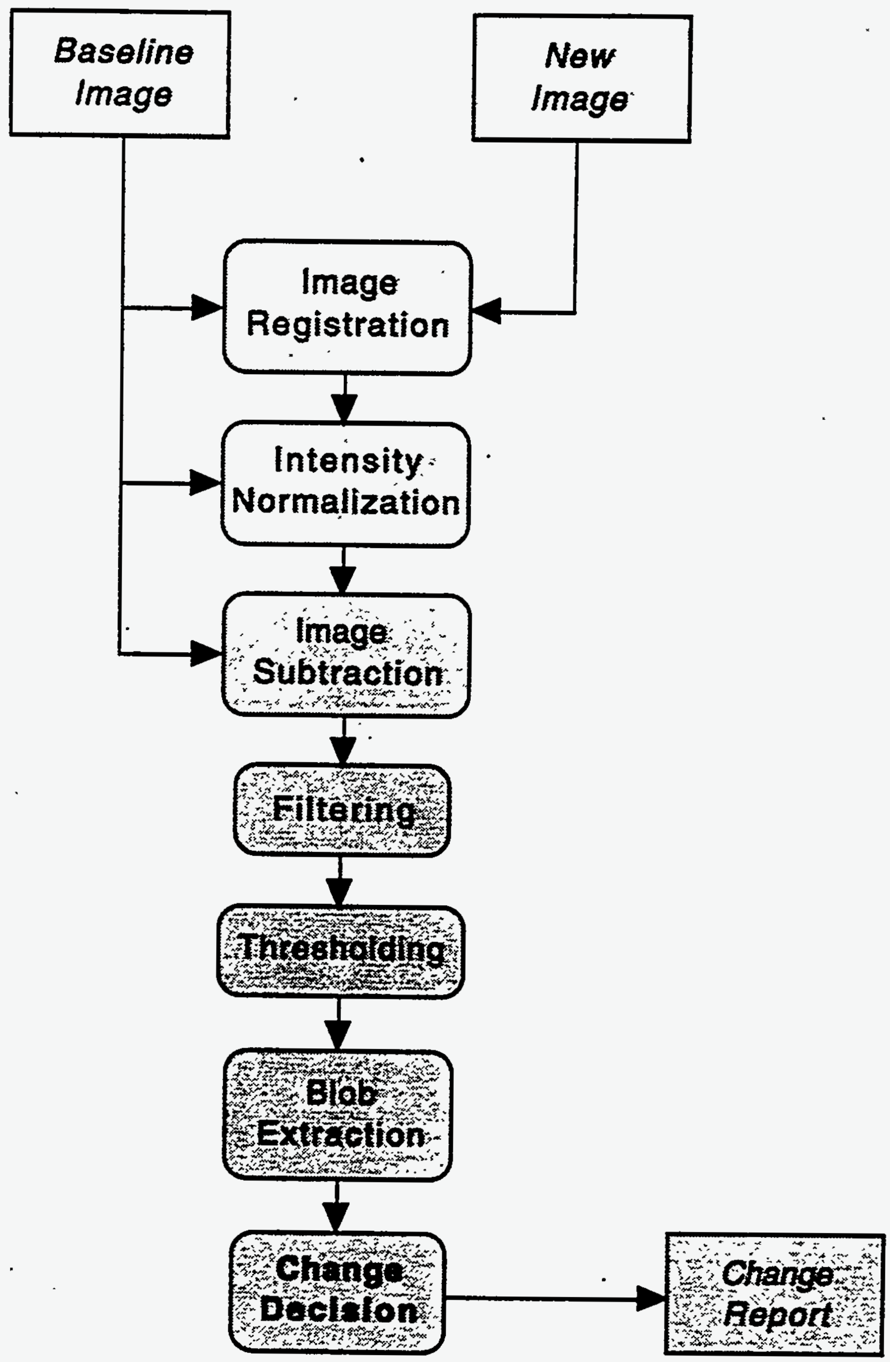


Figure 4.1: The Change Detection Procedure

6: **Blob Extraction:** Pixels which pass the threshold are then grouped into 'blobs' (i.e. collections of pixels forming a connected region).

7: **Change Decision:** The last step is to examine each of the 'blobs' and determine if any of them represent a change that is worth notifying an operator about. Some blobs may be too small to be a reliable indication of change, but may be recorded in a database so that on a subsequent visit the same region of the image can be checked to see if the apparent change has persisted.

Our principal tool for performing the image analysis steps described above is "IPLab Spectrum" from Signal Analytics, a Macintosh application with a broad suite of image processing functions as well as the ability to record and rerun a commonly used sequence of operations.

4.1. Dot Size

Images of the variable size dot patterns shown in Figure 3.8 were captured at two orientations: horizontal (that is, with the longer axis of the page wrapped horizontally around the drum so that dot size stays constant in the horizontal direction, but reduces in the vertical direction, as can be seen on the middle drum in Figure 3.1), and vertical.

The expected diameter in pixels of a dot on the drum, as a function of distance from the center is as follows:

$$dp = (f \cdot d) / (e \cdot (sd + dr\,(1 - \cos \alpha)))$$

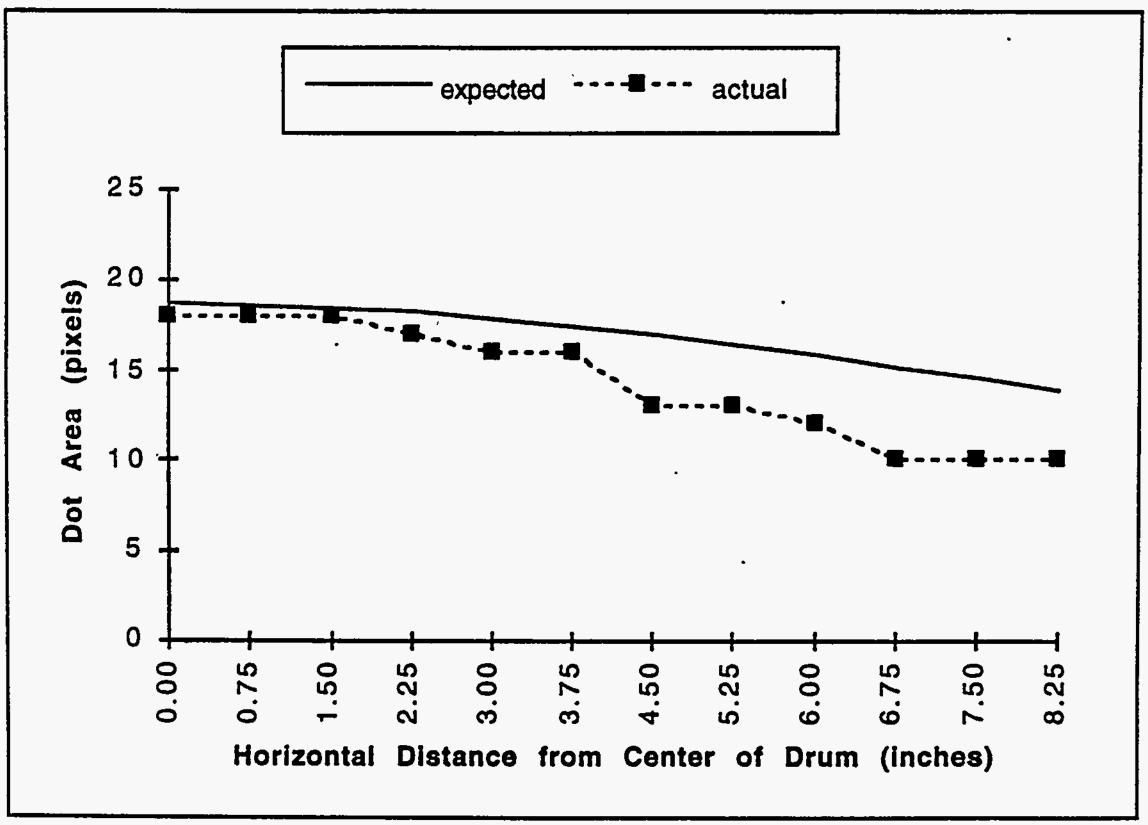


Figure 4.2: Dot area as a function of horizontal position

where

dp	=	dot size in pixels;
f	=	focal length;
d	=	physical size of the dot on the drum;
e	=	CCD element size
sd	=	stand-off distance;
dr	=	drum radius; and
α	=	the angular displacement of the dot from the center line of the drum.

IPLab was used to segment the image, label the dots, and measure area statistics on the dots. For the case of just the 1/4" dot (which is in the 6th row of the pattern), Figure 4.2 shows the expected and measured dot area as a function of the horizontal distance around the drum. Beyond 8.25" (21°) it became difficult to reliably extract the dots due to the curvature of the drum which causes a fall off in reflectance.

This result indicates that dot area approximately halves over its visible range, but still remains at a size that is distinguishable from noise. The fall-off in area is faster than anticipated from the geometrical analysis, due to fall off in contrast and to radial distortion (which reduces resolution in the periphery). The result implies that we can probably discard blobs that are smaller than 3 x 3 pixels in size.

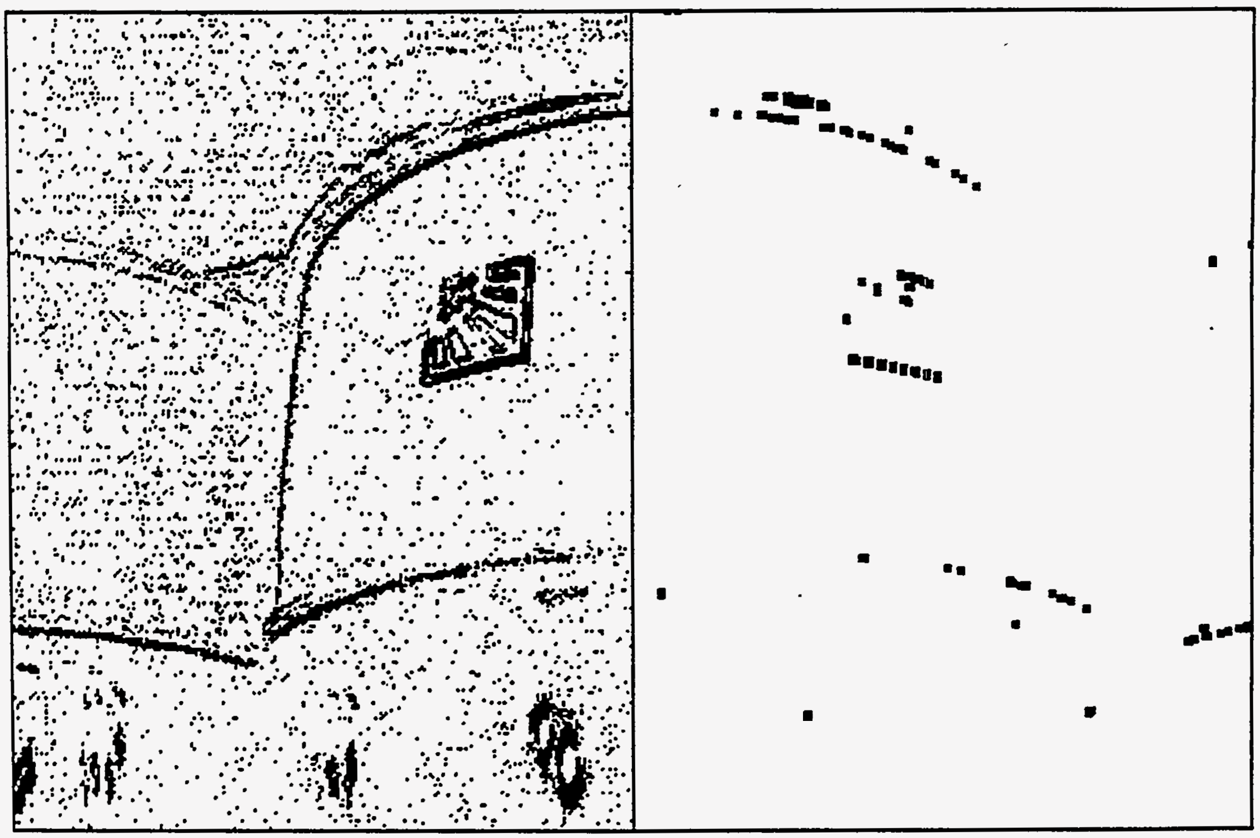


Figure 4.3: Left side - result of image subtraction for displaced camera
Right side - result of clutter removal using 3x3 filter

A well known image processing technique for achieving removal of unwanted small features is known as a morphological filtering. We tested the use of a 3 x 3 filtering kernel used in a dilation operation followed by a expansion operation (together referred to as a morphological "opening" operation). This is quite effective for removing insignificant clutter. To illustrate this we took two images with the camera moved by 1 inch (in the horizontal axis) between the images. Image changes are induced by the change in camera position. These two images were subtracted and the contrast highly exaggerated to produce the result shown in the left half Figure 4.3. The speckly pattern is the result of sensor noise. Several features can be distinguished because of the slightly different positions they appear in the two images due to the change in perspective: the outline of a drum and its neighbor, one face of a label, and blobs at the bottom of the image corresponding to reflections of the light sources. The right side of the figure shows what happens when a 3x3 erode & dilate operation is applied. Notice that the significant changes are still visible but the background noise has been removed.

There are other types of filtering that may also be appropriate for noise removal, such as median filtering. The choice of filtering technique will be investigated in subtask 2.3.

Figure 4.4 shows the results for dot area as a function of vertical position on the drum. The gap in the graph represents a region of the drum where no results were obtained. This corresponds to the upper rib on the drum. The dot pattern sheet was split across this rib. The variability in dot area is due to the sensitivity of the area calculation to the setting of the threshold. However the overall trend is for the dot area to reduce towards the top (or bottom) of the drum due to the reduction in image contrast and the reduced resolution (caused by radial distortion).

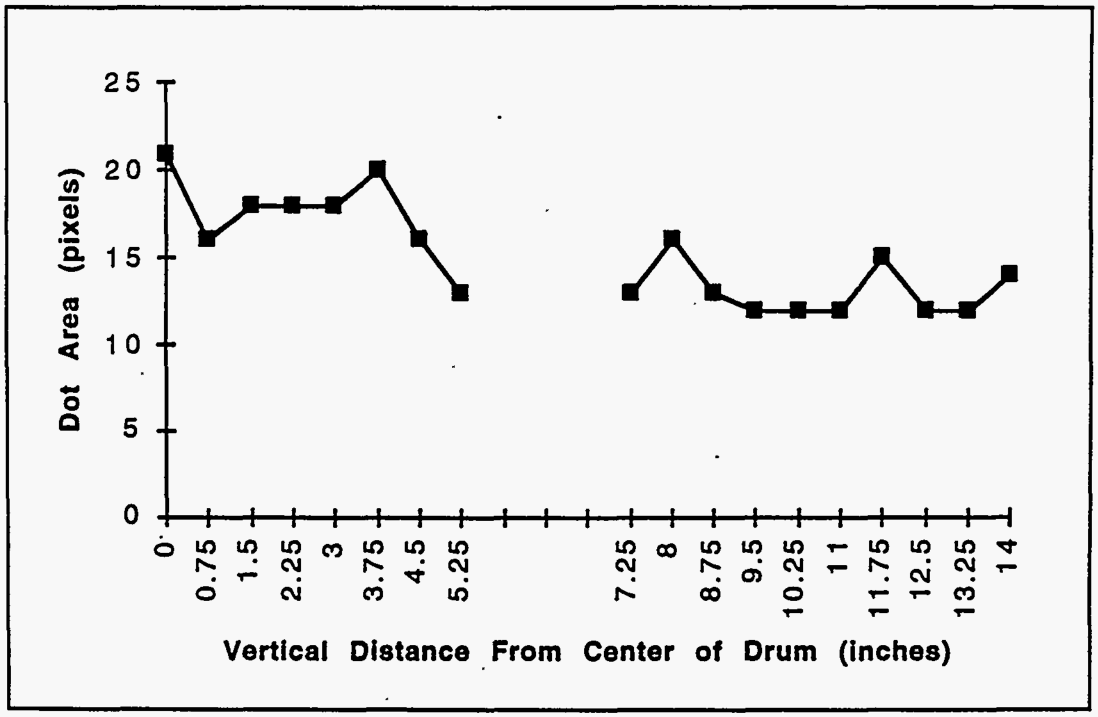


Figure 4.4: Dot area as a function of vertical position

4.2. Camera Positioning Sensitivity

The purpose of this part of the work was to measure the sensitivity of the change detection process to errors in the position and orientation of the camera with respect to the position the camera was in when the Baseline Image was captured.

From a geometrical point of view, the following equations were derived to estimate the maximum position deviation that could be tolerated:

$$Xmax = Ymax = dp\_max * e * sd / f$$

$$Zmax = dp\_max * e * (sd)^2 / (f * dh/2)$$

$$TILTmax = PANmax = \tan^{-1}(Xmax / sd)$$

$$ROLLmax = Xmax / (dh/2) \text{ radians}$$

where:

Xmax,
Ymax,
Zmax,
TILTmax,
PANmax,
ROLLmax = maximum error in the given dimension from the baseline position;

dp_max = diameter of maximum allowable false change in pixels (chosen as 3 from the results in Figure 4.2);

dh = drum height;

f = focal length;

e = CCD element size

sd = stand-off distance;

The values calculated for each of these are shown in Figure 4.5. These values assume no radial distortion. The effect of radial distortion was also investigated analytically (for the case of our 4.2 mm lens) and it was found that the errors introduced were not additive, and at worst, of the same order as that introduced by perspective distortion, and so do little to tighten the performance criteria.

These analytical results were then tested experimentally. A reference (baseline) image was captured first, and then a series of images in which the camera was moved along a single axis at a time to test sensitivity along each axis.

As described earlier, the test image (taken with the camera moved from the baseline position) must first be registered to remove any simple offset between the images. This was achieved automatically using IPLab. A script was developed that used an FFT based cross-correlation of a 128 x 64 pixel region around the center of the drum to compute the shift to be applied between the images. After the shift had been applied the images were then subtracted. We then experimented

Figure 4.5: Performance Criteria for Camera Positioning Repeatability

Camera Position Axis	X (left right)	Y (up-down)	Z (in-out)	Tilt	Pan	Roll
Performance Criteria	±0.15"	±0.15"	±0.2"	±0.8°	±0.8°	±0.5°

with varying a binary threshold on the image to determine what level of contrast was necessary to eliminate false changes and image noise. We found this contrast needed to be in the 10-20% range (i.e. intensity difference of 25-50 gray levels) to avoid picking up false changes. The choice of threshold will be studied further under subtask 2.4.

One important observation from these experiments was that the spot lights created bright glare points on the drum which were very sensitive to change in position because the lights moved with the camera in the Y and Z axes. This can be seen in Figure 4.3, where the elliptical shaped objects in the lower part of the image are due to specular reflections. These glare points could also obscure real changes because they tend to saturate the CCD pixels on which they are imaged. It will therefore be important that we use a diffuse light source on the mobile robot to reduce or eliminate these glare points.

This experiment verified that the calculated performance criteria matched reasonably well the behavior seen in the images. Clearly if we are able to build a system that can perform better than this limiting criteria by a reasonable margin then we can have higher confidence that we will minimize false detections.

4.3. Illumination Sensitivity of Change Detection

The purpose of this experiment was to determine what contrast between a dot and its background

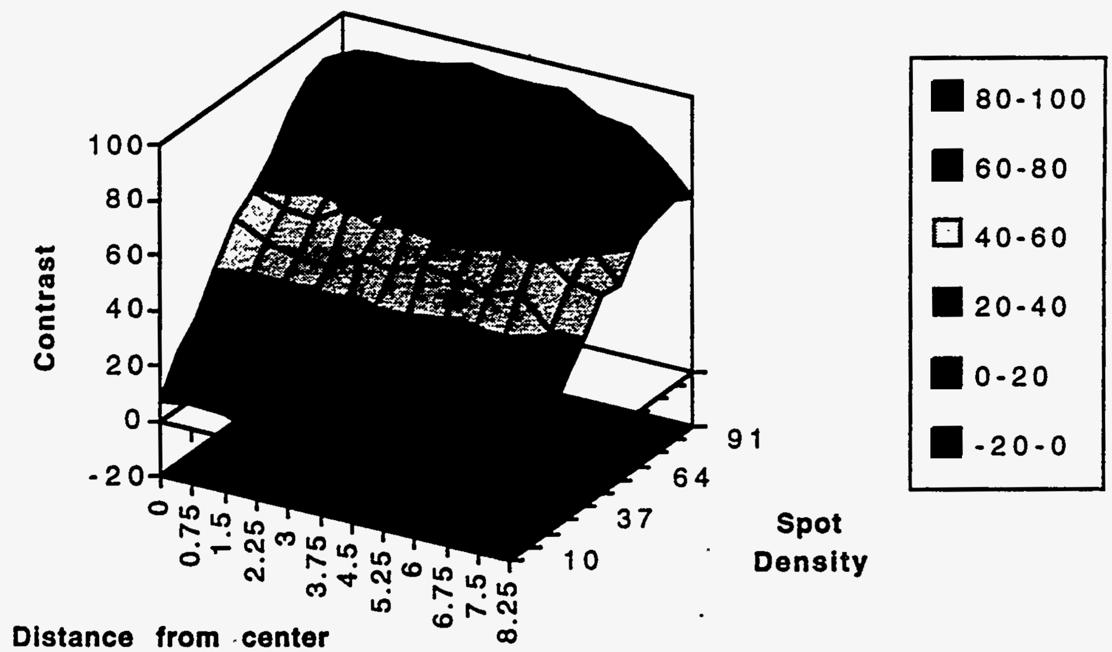


Figure 4.6a: Contrast as a function of Drum Position (100% spot - 81% surrounding)

was necessary in order to reliably detect it for the case where the illumination between a baseline image is slightly different from the illumination in an image captured at a later date. We were also interested in how this changed as a function of the dots position around the curved surface of the drum.

The dot pattern shown in Figure 3.9 was attached horizontally to the drum. The density of the dots ranges from 100% to 10% in 9% steps (the density value as defined by the drawing program used, and not necessarily a true density). One image of this was taken with the spot lights on full (100%), and second image was taken with the lights reduced to 81% of their full power. IPLab was then used to sample the gray level intensity of the interior and immediate surrounding of each dot.

Figure 4.6a illustrates the result of our experiment for the case of comparing the black dots in the bright (100%) image with the surrounding white pixels in the darker (81%) image. This can be thought of as corresponding to the case where a dot has appeared as a change on a white background but is being viewed under *brighter* conditions than the baseline image. Consequently, if the contrast of the dot is low it is possible for the pixel gray level on the dot to be very similar (or even brighter) than the corresponding pixels in the baseline image. This is why the graph dips below zero at one place. The conclusion for this case is that a spot density of at least 20% is needed in order to see a gray level difference of 30 (the choice of 30 as the threshold is determined by the next case).

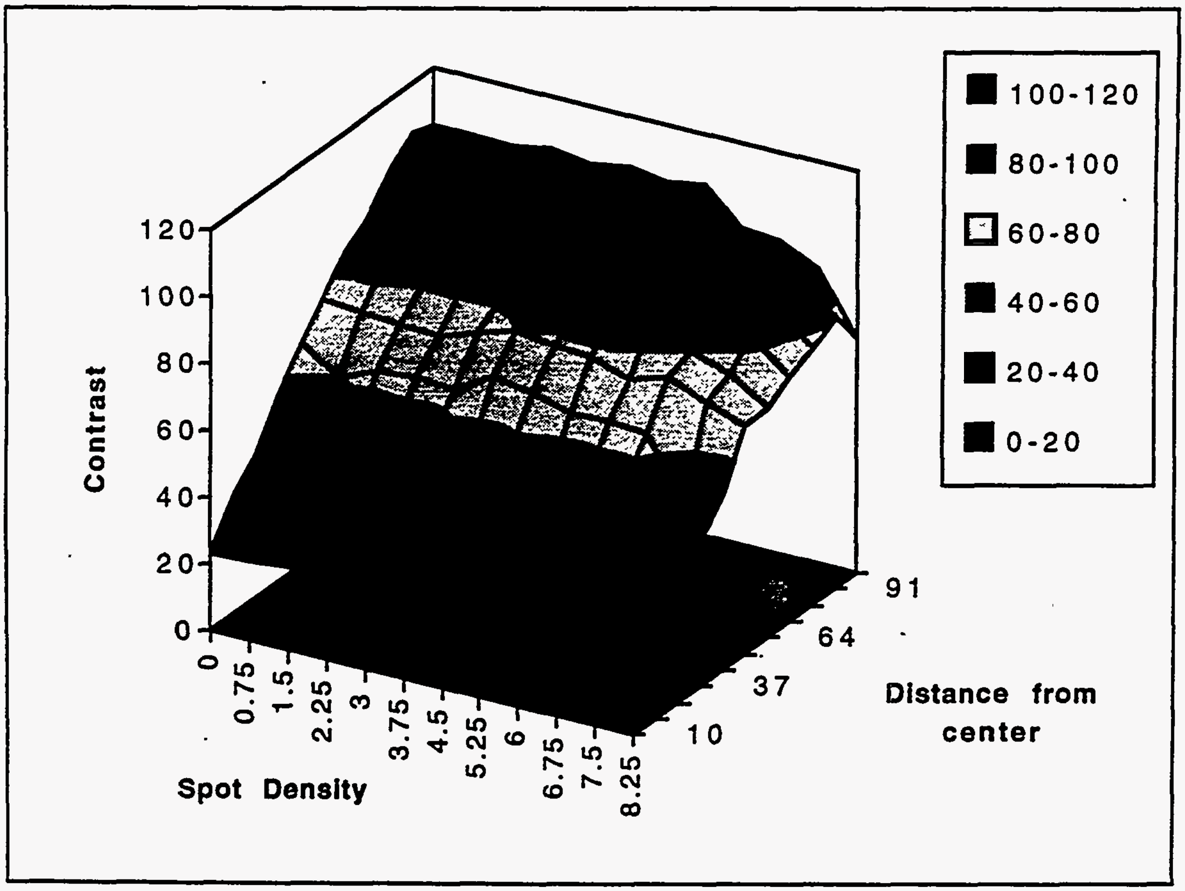


Figure 4.6b: Contrast as a function of Drum Position (100% surrounding - 81% spot)

Figure 4.6b considers the opposite case of comparing the dots in the darker image with the surrounding white pixels in the brighter image. This can be thought of as corresponding the case where a dot has appeared as a change on a white background but is being viewed under *dimmer* conditions than the baseline image. Consequently, even if there is no change at a given location in the image, there is still seen to be a difference due to the changing illumination. So the conclusion in this case is that the contrast threshold must be at least 30 gray levels to avoid seeing false changes due to the different illumination conditions.

The difficulty with this experiment is that the quantitative results are subject to many parameters including the distribution of illumination used, the effect on the lights of reducing power to them, and the response characteristics of the particular CCD (which is non-linear, and changes depending on the gamma correction setting). We also did not have the means to measure dot contrast directly (e.g. as determined with a densitometer). There are two things we will need to do to deal with all this variability: develop an illumination calibration procedure (so that the light source and sensor characteristics for a given set up are known, and a suitable contrast threshold chosen); and include an intensity normalization step (as described earlier) to reduce the effect of illumination variability.

4.4. Eliminating Ambient Illumination

As can be seen from the results above, a requirement of change detection via image subtraction is that there be consistent illumination on the drum from one visit to the next. There is one source of variability that we do not have any control over: the ambient illumination in the vicinity of the drum. One approach to minimizing the impact of changes in ambient illumination is to provide such a high level of illumination from the robot that any other background sources of illumination (such as the overhead lights in the warehouse) become insignificant relative to the robots illumination. While this may prove quite effective on the surface of the drum itself, it will not help with any parts of the field of view that are viewing well beyond the drum (such as distant background seen over the top of the drum, for a drum on the top of a stack). A further disadvantage of this approach is that it increases the power requirements on the robot which must operate off rechargeable batteries.

An alternative approach that does not require such a high level of controlled illumination is called ambient subtraction. Two images are taken in quick succession: an "ambient" image in which the robots lights are turned off, and a "ambient and lights" image in which the robots lights are turned on. By subtracting the "ambient" image from the "ambient and lights" image, the component of the illumination at each pixel due to the ambient illumination is eliminated.

A wrinkle in this apparently simple scheme is that the image gray level values have to first be corrected so that gray level value is directly proportional to the incident illumination level (an operation call linearization). Without this step, the subtraction does not produce the desired result due to the non-linear response of the CCD to different light levels.

4.4.1. Ambient subtraction test

To illustrate the non-linearity of the CCD sensor (and the importance of calibrating its luminosity response) we captured three images of the same scene under different lighting conditions:

1. ambient illumination only (light from overhead fluorescent lights)
2. spot lights only (no ambient illumination)
3. ambient illumination and spot lights

If the sensor were perfectly linear, then adding the first two images, and subtracting the third should result in a value of 0 at every pixel:

$$I(\text{ambient illumination only}) + I(\text{spot lights only}) - I(\text{ambient illumination and spot lights}) = 0$$

However the non-linearity of the sensor means that, for example, doubling the amount of light incident on a given pixel does not double the output; it may be greater or less than this. Figure 4.7 illustrates the intensity histogram for the result of the above addition and subtraction for the test images. Notice that the range of values is about 27 gray levels, which in some circumstances may be enough to introduce false detections of change. The secondary peak in Figure 4.7 is due to there being a large area of the image with a very similar gray level (the dark upper and lower regions of the drum).

In order to correct for this (so that it is valid to subtract out the ambient illumination) we need to develop an automatic method for the camera system to calibrate its luminosity response.

4.4.2. Sources of short-term variability in ambient illumination

In order for ambient subtraction to work, the ambient illumination must not change significantly between the capture of the two images. Figure 4.8 is the histogram produced from subtracting two images of the same scene taken in quick succession without any intentional change in the lighting conditions. Ideally the two images would be identical, but the histogram shows that there is some variability. There are at least three sources of short-term variability in the ambient illumination to consider:

1. Beating between fluorescent lights and video frame rate.
   Slight differences between the flicker rate of the overhead lights and the frame rate of the camera can result in short term changes. This can be alleviated by using an integration time for the frame capture that is about twice as long as the period of the ambient flicker.

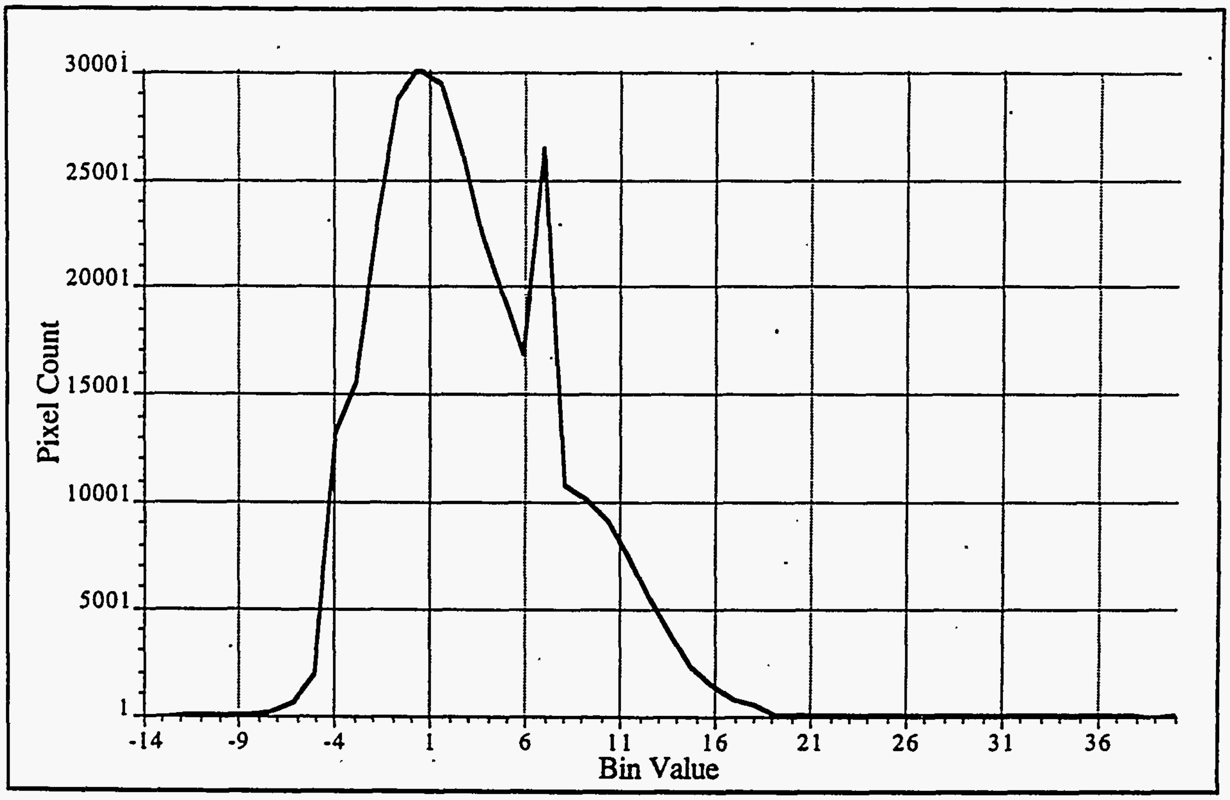


Figure 4.7: Histogram of Difference between arithmetic and actual light addition. (each Bin Value is one gray level)

2. Electrical noise.
   There are various sources of electrical noise in the camera, video transmission, and frame grabber. By selecting a good quality CCD camera, transmitter-receiver, and frame grabber, this should be reducible to a low level.

3. Sudden changes in illumination (e.g. failure of a nearby fluorescent).
   While this is unlikely, it could happen. If it was a concern, two ambient images could be obtained either side of the "ambient and lights" image and checked to make sure that there had not been any significant change between them.

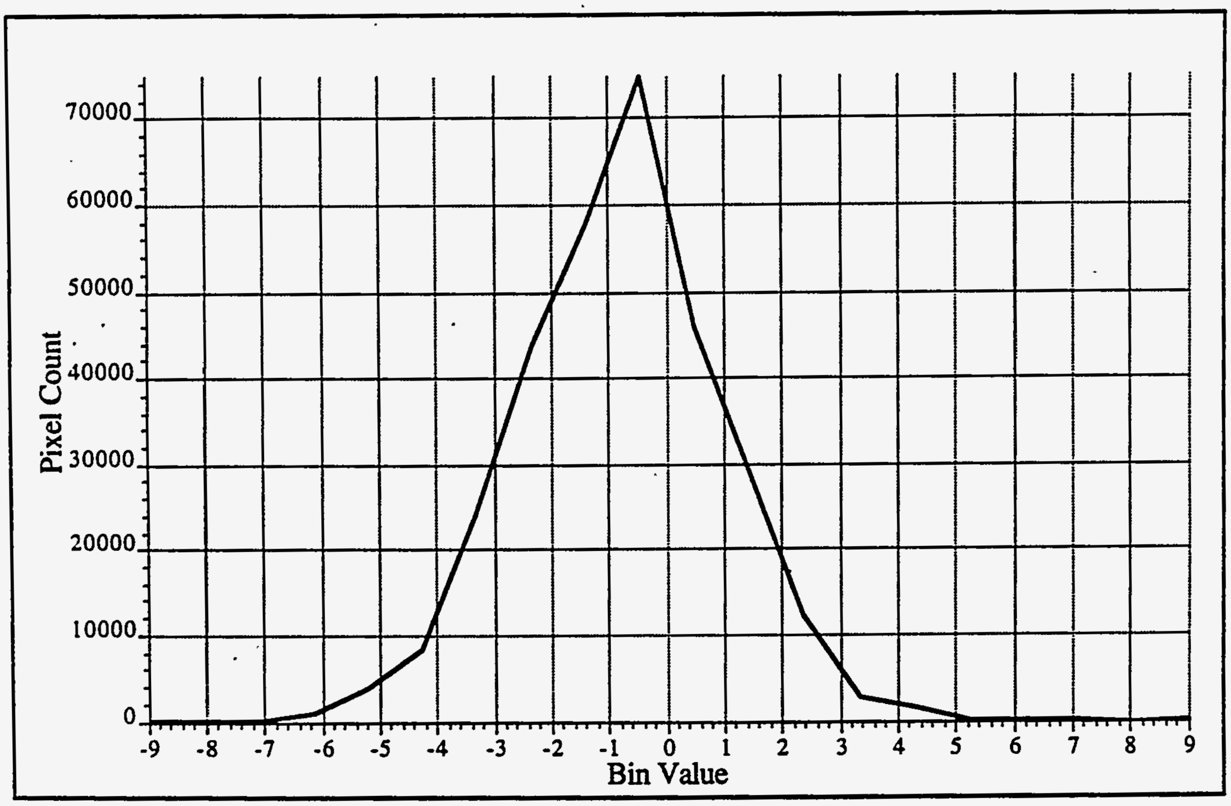


Figure 4.8: Histogram of Image. "Noise"
(each Bin Value is one gray level)

5. Vision System Experiments

The objective of this set of experiments was to determine what level of performance we could expect from the vision system (Eagle Eye), and to verify that its performance was within the criteria specified in Figure 4.5.

The nótion of repeatability is illustrated in Figure 5.1. A cross hair indicates the position at which the baseline image was captured for a particular drum. Eagle Eye's measurement of this position is recorded along with the baseline image. The absolute accuracy of this measurement is not of primary concern (although it is important that Eagle Eye be able to guide the camera positioning system to a position with sufficient accuracy that the entire drum be visible in the image while at the same time ensuring that the camera is not bumping up against the drum behind it in on the other side of the aisle from the drum of interest). What is important is that Eagle Eye be able to provide the robot with a measurement of position that is highly *repeatable* (i.e. consistent), so that the camera can be placed back at the same positioned with respect to the label on the drum upon each later visit to the drum. As explained earlier in Section 4.2 (and defined in detail in Figure 4.5), change detection based on image subtraction will not work unless the two views of the drum are taken from close to the same viewing point. This upper limit on positioning error is illustrated in Figure 5.1 by the large circle. Eagle Eye's repeatability performance (as illustrated by the smaller inner circle) must be better than this upper limit. (Note that the size of the circles in Figure 5.1 is highly exaggerated for illustrative purposes only).

5.1. Repeatability

The purpose of the repeatability experiments was to determine how reliably the camera could be repositioned in each axis of position and orientation. We were also interested to compare results for a label placed at the center of the drum versus at the top of the drum.

To test repeatability, the camera was moved through small increments along one axis at a time. Eagle Eye's output for the position should track the changing axis while remaining constant in the

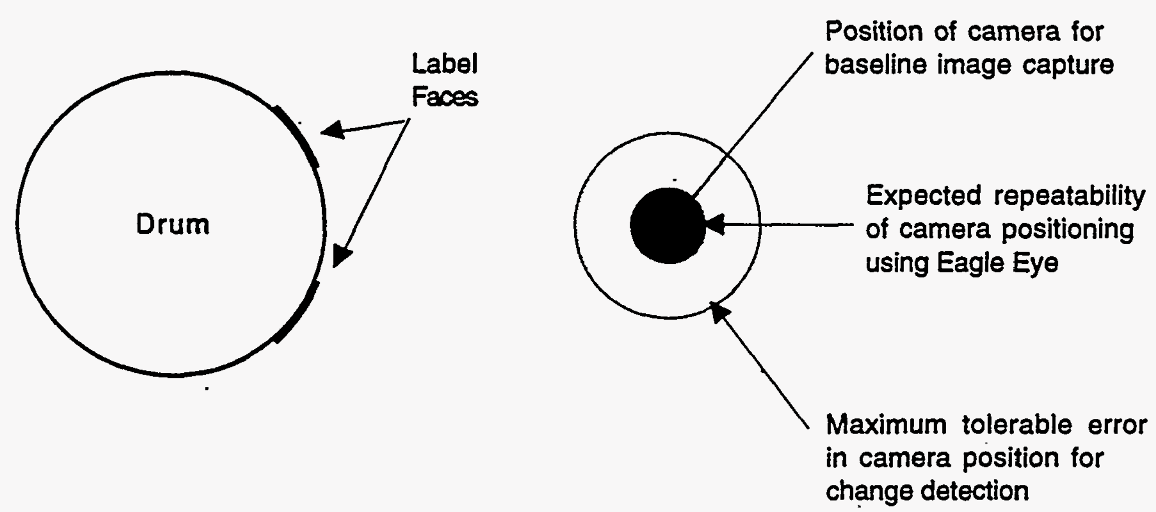


Figure 5.1: Repeatability of Camera Positioning (plan view; not to scale)

Figure 5.2: Results of Repeatability Experiments (for 2.5" face)

	Middle Label						Top Label					
Measured Variance for each axis ⇒ Motion Axis ⇓	X" (left-right))	Y" (up-down)	Z" (in-out)	X° (tilt)	Y° (pan)	Z° (roll)	X" (left-right)	Y" (up-down)	Z" (in-out)	X° (tilt)	Y° (pan)	Z° (roll)
X	0.04	0.02	0.01	1.00	0.30	0.10	0.09	0.03	0.09	1.00	0.90	0.70
Y	0.03	0.04	0.05	0.80	0.40	0.10	0.04	0.02	0.07	0.50	0.90	0.40
Z (2.5")	0.04	0.11	0.08	1.50	0.70	0.10	0.07	0.12	0.19	1.40	1.20	0.50
Z (6")	0.05	0.09	0.17	1.60	0.60	0.10	0.09	0.09	0.33	1.60	1.50	0.70
Pan	0.03	0.17	0.07	1.80	0.70	0.30	0.04	0.25	0.09	1.00	1.20	0.70
Tilt	0.03	0.03	0.05	0.50	0.10	0.10	0.06	0.02	N/A	0.60	0.70	0.40
Summary (expected performance)	±0.03	±0.03	±0.08	±0.6°	±0.4°	±0.2°	±0.05	±0.05	±0.1	±0.8°	±0.6°	±0.4°
Optical Bench Accuracy	±0.02	±0.02	±0.03	±0.25	±0.25	Axis Fixed	±0.02	±0.02	±0.03	±0.25	±0.25	Axis Fixed

other axes (so this was not strictly testing repeatability by revisiting the same point, but inferring repeatability by examining the consistency of Eagle Eye's output while one position or orientation axis was changing). For the position axes this simply means moving the camera along one corresponding bench axis. However for the case of pan and tilt about the origin of the marker, this required calculating an appropriate movement about the other bench axes to ensure that the Z distance along the optical axis of the camera did not change. Our experimental set-up did not allow us to make changes to the roll axis, but we were able to gain some idea of the stability of this result by observing the fluctuations on the result while making changes in other axes.

The detailed results of these experiments are presented in Appendix A3. The results for each experiment are summarized below in Figure 5.2 for the first set of labels used that had a 2.5" square face pattern. The table lists the total range of deviation for each axis from the expected deviation (or lack of deviation for any axes along which there was not supposed to be any motion). The summary row is an interpretation of these results in terms of the expected local repeatability (within a 2" x 2" x 2" volume) in light of the bench's accuracy, and the likely errors introduced by the multi-axis bench motions required to simulate pan and tilt about the middle markers origin. Below the summary row is the estimated accuracy of the optical bench itself for each axis. Note that for some axes (X, Y, and pan) the accuracy implied by the experiments is close to the accuracy of the optical bench, and so it is possible that the actual repeatability is higher than the value shown.

We had expected that the worst axis (in terms of conformance with the performance criteria) would be the tilt axis, because along this axis the label length is small compared to the total image size, and so there is a limited baseline upon which Eagle Eye can make its measurement. The results confirmed this expectation, and showed us that a 2.5" face on the label was too small to meet the performance criteria. This face size was also too small from the point of view of reliably tracking a label placed at the top of the drum. The drum curvature results in errors in the calculation of the corners of the faces because the corner calculations are based on fitting straight lines to the borders. It should also be noted that the repeatability results, especially for the top label, may be degraded by the radial distortion and poorer focus in the periphery.

We then tried a face size close to the maximum size that we expected to be able to use: 4". We repeated the tilt experiment and obtained a result of 0.1° accuracy for tilt (which is well within the performance criteria), but found that the curvature for such a large face resulted in unacceptable results for the label placed near the top of the drum.

An in-between face size of 3.2" was then tried and this produced good results (0.2°) for tilt accuracy with respect to a label in the middle of the drum, but still experienced some difficulty with reliably locking onto both faces of a label placed near the top of the drum due to the label curvature. If labels are to be placed this high (or low) on the drum, we will need to explore this problem further to improve tracking reliability.

In conclusion, a face size of 3.2" for the label results in a level of repeatability that is within spec. with respect to orientation and excellent with respect to position for a label placed on the middle of the drum, while a label placed near the top or bottom of the drum is problematic due to drum curvature.

5.2. Illumination Sensitivity

Eagle Eye is less sensitive to changes in illumination than the change detection because the labels are designed to have high contrast. We expect Eagle Eye to be able to cope with changes in the range of 20 - 30%. However no systematic experiments were performed on this, and so this should be a subject of further study during the development of the Application System in Phase 1B.

5.3. Operational Volume

This experiment determined the bounds on the cameras position (with respect to a nominal central location) that ensure that Eagle Eye can still reliably see both faces of the label assuming that the camera is within a few degrees of being level.

Operational Volume:

left-right: ±6"

up-down: ±12"

in-out: ±6"

The significance of this volume is that this is the region the robot must navigate the camera within before Eagle Eye can start providing the robot with accurate information for final repositioning. Note however that Eagle Eye can still produce useful, though less accurate output outside of this volume if it is able to see one face on the label.

6. Discussion

The purpose of this section is to briefly comment on the results of the analysis and experiments, note any unresolved issues, and note any implications for the remainder of Phase 1 and for the proposed Phase 2.

6.1. What did we learn?

Illumination

We confirmed our expectations that specular reflection poses a problem for spot lighting, and recommend the use of diffuse light sources on the robot.

We experienced some difficulty with the illumination (contrast) experiments in terms of interpreting the results and defining what level of contrast can reasonably be distinguished as a genuine change. Overall we felt that the 10% contrast level may be optimistic, with 20% a more reasonable change detection level.

Eagle Eye tracking performance

The good positional (X,Y,Z) repeatability was encouraging, especially given the level of radial distortion that Eagle Eye needed to correct for. The results appeared to be well within the limits set by the performance criteria.

As expected, the tilt and pan performance were the poorest, leading to experiments with different label sizes. The performance was within spec. for the middle label, but the curvature of the upper label caused problems in reliable label reading and position calculation. If any labels are to be placed close to the top or bottom of drums we will need to consider how we can redesign the label to improve Eagle Eye's reliability.

The operational volume (i.e. the region that the robot has navigate the camera within) appears quite reasonable, so that high accuracy is not demanded of the navigation.

6.2. What issues remain unresolved?

Transmission Quality Requirement

No thorough testing has yet been performed for the video transmission subsystem. There is some concern that it might be difficult to get clean transmission in the warehouse environment with so much metal around. Digital or optical (IR) video transmission techniques may need to be explored (Astra Aerospace has tested Eagle Eye on images compressed with JPEG and got good results).

Impact of component change-out

Our choice of a high quality camera and frame grabber leads us to believe that there would be negligible impact of swapping out these components. However the lens is an area for concern, and we believe it is likely to be important that we obtain much higher quality lenses than the once used in the experiments, and that the calibration parameters for a lens be associated with any images captured using that lens.

Label attachment technique

Prior to phase 2 we need to give some thought to the problem of attaching labels to a large number of drums. Issues include the type of adhesive, the type of label material, the printing process, and the alignment requirements.

How will color imagery improve / complicate change detection?

The experiments in phase 1A were based on a black and white camera. In phase 1B we will be considering how color information can be used to assist in change detection.

6.3. What are the implications for phase 1? phase 2? beyond?

Label Design

Our current recommendation for the label design is one with two 3.2" square face patterns. Several other label design options were noted in Section 2.2.4 that may be worth considering. Adding a third face in the center of the label would allow the system to easily obtain two images of the drum from left and right off-center positions, thus obtaining a better coverage. Another option is to repeat the face pattern on a long label that wraps around the entire drum. This would allow the drum to be removed from a pallet and replaced without any concern for the drums orientation. It would also enable Eagle Eye to be of use to an automatic drum handling system.

Lens Selection

The results re. radial distortion show that the longest focal length possible should be chosen for whatever aisle we are actually likely to be in, in order to minimize radial distortion. We also recommend that a high quality lens be purchased in order to minimize radial distortion and loss of focus in the periphery.

Positioning accuracy required of camera pan-tilt-translation

The performance criteria listed in Table E1 define the positioning control required of the camera positioning mechanism.

Motion stability

Camera motion is a problem for interlaced video because the image is captured as two fields: one representing the odd image lines and the other representing the even image lines. The time delay between fields (1/60th of a second) can result in misregistration between the two fields in any part of the image where there is motion (such as during the movement of the camera positioning mechanism). This problem can be alleviated by using a strobe light or a frame transfer camera (although we are unlikely to be able to obtain the latter in the form of a 3 CCD color camera).

Illumination control

Our results appear to indicate that the illumination should not fluctuate by more than about 5-10%, although we have not yet experimented with intensity normalization techniques which may loosen this requirement. Calibration of the CCD intensity response is needed for the ambient background subtraction technique to work.

Note that strobing and / or ambient image subtraction requires that the light source be under computer control.

An important consideration in the design of the illumination system is that the field of view of the camera is so wide that an effect known as 'cosine fall-off' becomes significant (as shown in Figure 6.1). This is a result of the inverse square law for radiation. For a lens with a field of view of 90° the relative luminosity measured for a flat field drops to half in the periphery (a flat field is a planar light source perpendicular to the camera's optic axis, and having even light output over its surface). The illumination will therefore need to be designed to offset this cosine fall-off.

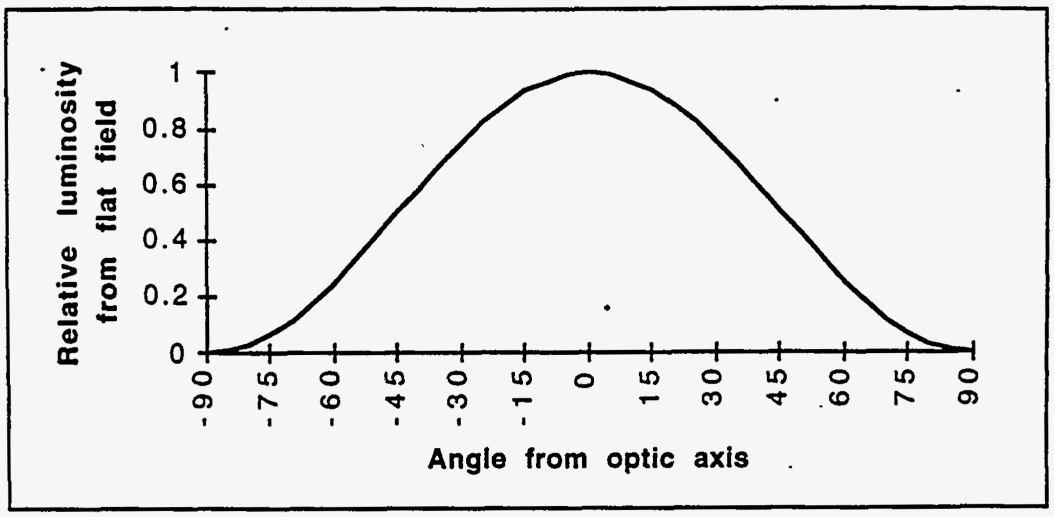


Figure 6.1: Cosine Fall-off

A. Appendices

A1. Label Size Calculations

Label size analysis - 2.5" 12/13/94

Drum height:	**dh**	87.63 cm	**34.5 inches**
Drum diameter:	**dd**	57.785 cm	**22.75 inches**
Drum radius:	dr	28.893 cm	11.375 inches
Drum circumference:	dc	181.537 cm	71.471 inches
Stand-off distance:	**s**	46.295 cm	**18.226 inches**
Drum angular height:	dah	1.516 radians	86.847 degrees
Drum angular width:	daw	0.789 radians	45.197 degrees
Interior grazing angle:	iga	1.176 radians	67.401 degrees
Coverage:		37.45%	
Lens focal length:	f	0.42 cm	4.2 mm
CCD Width:	w	0.795 cm	0.313 inches
CCD Width:	**p**	**768. pixels**	
CCD Element Width:	**e**	0.001 cm	**10.352** µm
Face image width:	**i**	**45. pixels**	59.66
Faces around drum:	**faces**	**8.**	
Face center offset angle:	**gamma**	0.393 radians	**22.5 degrees**
Face width (angle):	**theta**	**0.221 radians**	12.672 degrees
Face edge offset angle:	delta	0.282 radians	16.164 degrees
dt/st		0.279	
dp/sp		0.28	
Solve for 0 by adjusting theta--->			
Diff. of label angle and drum angle:		0.673 radians	38.566 degrees
Check:	OK		
Image position of drum side:		168.88 pixels from centre	
Image position of drum top:		384 pixels from centre	
Image position of inner edge:		68.796 pixels from centre	
Image position of outer edge:		113.355 pixels from centre	
Check:		*** face width in pixels not consistent	
Curvature depth:		0.704 cm	
Curvature ratio:		11.01%	
Face width (cm):		6.39 cm	2.516 inches
Face separation (cm):		16.302 cm	6.418 inches
Two-Face Label Width (cm):		29.082 cm	11.45 inches
Check:	OK		

Label size analysis - 3.195" 12/13/94

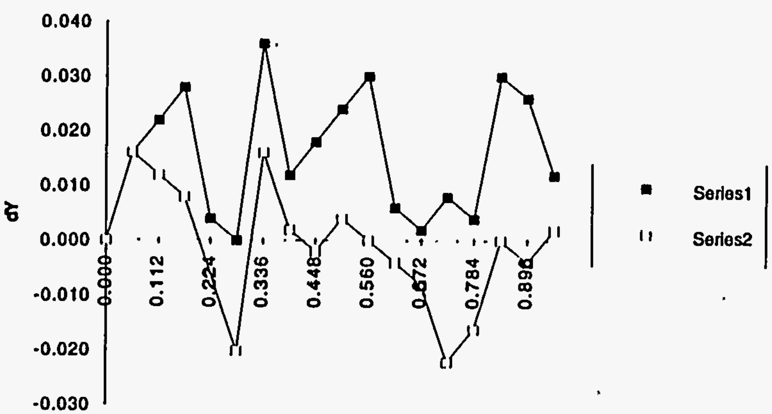
Drum height:	dh	87.63 cm	**34.5 inches**
Drum diameter:	**dd**	57.785 cm	**22.75 inches**
Drum radius:	dr	28.893 cm	11.375 inches
Drum circumference:	dc	181.537 cm	71.471 inches
Stand-off distance:	**s**	46.295 cm	**18.226 inches**
Drum angular height:	dah	1.516 radians	86.847 degrees
Drum angular width:	daw	0.789 radians	45.197 degrees
Interior grazing angle:	iga	1.176 radians	67.401 degrees
Coverage:		37.45%	
Lens focal length:	f	0.42 cm	4.2 mm
CCD Width:	w	0.795 cm	0.313 inches
CCD Width:	**p**	**768. pixels**	
CCD Element Width:	**e**	0.001 cm	**10.352 µm**
Face image width:	**i**	**56.46 pixels**	59.66
Faces around drum:	**faces**	**8.**	
Face center offset angle:	**gamma**	0.393 radians	**22.5 degrees**
Face width (angle):	**theta**	**0.281 radians**	16.093 degrees
Face edge offset angle:	delta	0.252 radians	14.453 degrees
dt/st		0.292	
dp/sp		0.292	
Diff. of label angle and drum angle:		0.643 radians	36.855 degrees
Check:	OK		
Image position of drum side:		168.88 pixels from centre	
Image position of drum top:		384 pixels from centre	
Image position of inner edge:		61.977 pixels from centre	
Image position of outer edge:		118.437 pixels from centre	
Check:	OK		
Curvature depth:		1.132 cm	
Curvature ratio:		13.95%.	
Face width (cm):		8.115 cm	3.195 inches
Face separation (cm):		14.577 cm	5.739 inches
Two-Face Label Width (cm):		30.807 cm	12.129 inches
Check:	OK		

A2. Eagle Eye Repeatability Experiments

X accuracy - experiment #1				94/12/2											
Set Pt.	Z	22.46													
Sample #	Set Pt. X	Label 1 X	Y	Z	X°	Y°	Z°	Label 2 X	Y	Z	X°	Y°	Z°	Label 1 dX	Label 2 dX
0	0.000	-0.05	-0.04	-21.87	0.0	-0.5	90.4	-12.45	-0.19	-21.98	-1.1	0.4	91.2	0.000	0.000
1	0.056	-0.12	-0.03	-21.87	-0.6	-0.7	90.4	-12.53	-0.19	-22.00	-1.5	0.0	91.0	-0.014	-0.024
2	0.112	-0.16	-0.02	-21.87	0.4	-0.4	90.3	-12.58	-0.19	-22.00	-1.8	-0.2	90.9	0.002	-0.018
3	0.168	-0.22	-0.03	-21.87	0.4	-0.4	90.3	-12.65	-0.20	-22.01	-1.8	-0.3	90.8	-0.002	-0.032
4	0.224	-0.28	-0.03	-21.88	0.1	-0.5	90.3	-12.70	-0.20	-22.02	-1.9	-0.2	90.9	-0.006	-0.026
5	0.280	-0.33	-0.03	-21.87	0.3	-0.4	90.3	-12.77	-0.20	-22.03	-1.9	-0.3	90.8	0.000	-0.040
6	0.336	-0.39	-0.03	-21.88	-0.2	-0.5	90.4	-12.82	-0.19	-22.01	-1.7	0.1	91.0	-0.004	-0.034
7	0.392	-0.46	-0.02	-21.88	0.4	-0.4	90.3	-12.88	-0.17	-22.00	-1.2	0.6	91.3	-0.018	-0.038
8	0.448	-0.50	-0.03	-21.87	0.3	-0.4	90.3	-12.91	-0.18	-22.01	-1.3	0.5	91.3	-0.002	-0.012
9	0.504	-0.55	-0.03	-21.88	0.3	-0.5	90.3	-12.97	-0.18	-22.01	-1.2	0.6	91.5	0.004	-0.016
10	0.560	-0.60	-0.03	-21.88	0.1	-0.5	90.3	-13.00	-0.18	-22.00	-1.3	0.6	91.3	0.010	0.010
11	0.616	-0.66	-0.03	-21.87	0.0	-0.4	90.3	-13.09	-0.18	-22.00	-1.6	0.6	91.3	0.006	-0.024
12	0.672	-0.71	-0.03	-21.87	-0.1	-0.5	90.3	-13.14	-0.19	-22.04	-1.8	0.1	91.1	0.012	-0.018
13	0.728	-0.79	-0.03	-21.87	-0.2	-0.5	90.3	-13.14	-0.20	-22.06	-1.9	-0.1	91.0	-0.012	0.038
14	0.784	-0.82	-0.03	-21.88	0.3	-0.4	90.3	-13.23	-0.20	-22.05	-1.9	-0.2	91.0	0.014	0.004
15	0.840	-0.89	-0.04	-21.88	0.0	-0.6	90.3	-13.34	-0.20	-22.05	-1.9	-0.1	91.0	0.000	-0.050
16	0.896	-0.93	-0.03	-21.88	0.1	-0.5	90.3	-13.39	-0.20	-22.07	-2.1	-0.2	91.0	0.016	-0.044
17	0.952	-0.98	-0.03	-21.87	0.2	-0.4	90.4	-13.43	-0.20	-22.07	-2.1	-0.2	91.0	0.022	-0.028
	Max - Min		0.02	0.01	1.00	0.30	0.10		0.03	0.09	1.00	0.90	0.70		
	Sd		0.00	0.01	0.26	0.08	0.04		0.01	0.03	0.32	0.35	0.20		

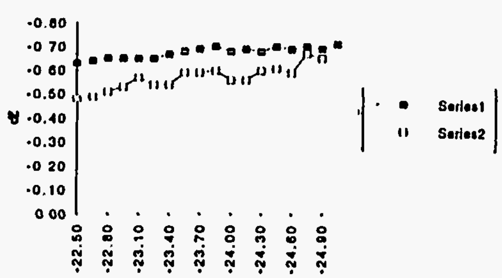
	Label 1 dX	Label 2 dX
Min	-0.018	-0.050
Max	0.022	0.038
Max - Min	0.040	0.088
Mean	0.002	-0.020
Sd	0.0106	0.0217

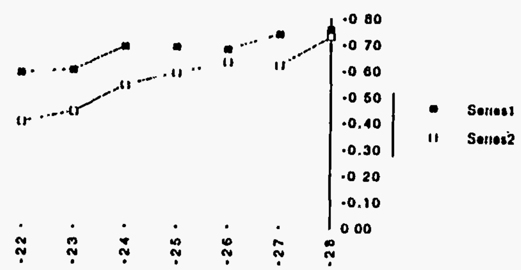
Y accuracy - experiment #1				94/12/2												
Set Pt.	Z	22.46														
Sample #	Set Pt.	Label 1						Label 2							Label 1	Label 2
	Y	X	Y	Z	X'	Y'	Z'	X	Y	Z	X'	Y'	Z'		dY	dY
0	0.000	-0.06	0.01	-21.88	-0.4	-0.4	90.3	-12.50	-0.17	-22.02	-1.7	-0.3	91.0		0.000	0.000
1	0.056	-0.05	0.05	-21.88	-0.4	-0.3	90.3	-12.50	-0.13	-22.02	-1.6	-0.2	91.0		0.016	0.016
2	0.112	-0.06	0.10	-21.87	-0.6	-0.4	90.3	-12.48	-0.07	-22.01	-1.7	-0.3	90.9		0.022	0.012
3	0.168	-0.06	0.15	-21.87	-0.7	-0.5	90.3	-12.49	-0.01	-22.02	-1.7	-0.2	91.0		0.028	0.008
4	0.224	-0.06	0.23	-21.84	-0.1	-0.2	90.3	-12.48	0.06	-22.00	-1.6	-0.1	90.9		0.004	-0.006
5	0.280	-0.05	0.29	-21.87	-0.1	-0.4	90.3	-12.47	0.13	-21.99	-1.3	0.2	91.1		0.000	-0.020
6	0.336	-0.06	0.31	-21.87	-0.7	-0.5	90.3	-12.47	0.15	-21.99	-1.3	0.3	91.2		0.036	0.016
7	0.392	-0.06	0.39	-21.84	-0.1	-0.2	90.3	-12.47	0.22	-22.00	-1.6	0.0	90.9		0.012	0.002
8	0.448	-0.06	0.44	-21.85	-0.2	-0.5	90.3	-12.47	0.28	-21.98	-1.6	0.1	90.9		0.018	-0.002
9	0.504	-0.07	0.49	-21.85	-0.6	-0.3	90.3	-12.46	0.33	-21.97	-1.2	0.5	91.3		0.024	0.004
10	0.560	-0.07	0.54	-21.84	-0.4	-0.4	90.3	-12.46	0.39	-21.96	-1.2	0.5	91.2		0.030	0.000
11	0.616	-0.07	0.62	-21.87	-0.6	-0.4	90.3	-12.48	0.45	-22.00	-1.6	-0.1	90.9		0.006	-0.004
12	0.672	-0.08	0.68	-21.86	-0.9	-0.4	90.4	-12.49	0.51	-22.00	-1.6	-0.1	90.9		0.002	-0.008
13	0.728	-0.07	0.73	-21.85	-0.6	-0.6	90.4	-12.49	0.58	-22.00	-1.4	0.1	91.1		0.008	-0.022
14	0.784	-0.07	0.79	-21.84	-0.4	-0.5	90.4	-12.50	0.63	-22.01	-1.7	0.0	91.1		0.004	-0.016
15	0.840	-0.07	0.82	-21.86	-0.5	-0.5	90.3	-12.46	0.67	-21.95	-1.2	0.6	91.2		0.030	0.000
16	0.896	-0.07	0.88	-21.85	-0.4	-0.5	90.4	-12.47	0.73	-21.96	-1.3	0.3	91.1		0.026	-0.004
17	0.952	-0.07	0.95	-21.83	-0.2	-0.3	90.3	-12.50	0.78	-21.99	-1.6	0.1	91.1		0.012	0.002
	Max-Min	0.03		0.05	0.80	0.40	0.10	0.04		0.07	0.50	0.90	0.40	Min	0.000	-0.022
	Sd	0.01		0.02	0.23	0.11	0.04	0.01		0.02	0.19	0.28	0.13	Max	0.036	0.016
														Max - Min	0.036	0.038
														Mean	0.015	-0.001
														Sd	0.012	0.011



Sample #	Set Pt Z	Label 1 X	Y	Z	X*	Y*	Z*	Label 2 X	Y	Z	X*	Y*	Z*		Label 1 dZ	Label 2 dZ
Z accuracy - experiment #1				94/12/2												
0	-22.50	-0.06	0.01	-21.87	-0.5	-0.2	90.3	-12.49	-0.17	-22.02	-1.5	0.1	91.2		-0.63	-0.48
1	-22.65	-0.05	0.02	-22.01	-0.2	-0.2	90.3	-12.49	-0.16	-22.16	-1.4	0.1	91.1		-0.64	-0.49
2	-22.80	-0.05	0.03	-22.15	-0.1	-0.4	90.3	-12.48	-0.14	-22.29	-1.5	0	91.1		-0.65	-0.51
3	-22.95	-0.04	0.03	-22.30	0.5	-0.3	90.3	-12.48	-0.15	-22.42	-1.5	-0.3	90.9		-0.65	-0.53
4	-23.10	-0.06	0.01	-22.45	-0.1	-0.4	90.3	-12.46	-0.14	-22.53	-0.8	0.5	91.3		-0.65	-0.57
5	-23.25	-0.06	0.01	-22.60	-0.3	-0.6	90.3	-12.49	-0.15	-22.71	-1.1	-0.1	91.0		-0.65	-0.54
6	-23.40	-0.05	0.03	-22.73	0.6	-0.3	90.3	-12.49	-0.15	-22.86	-1.4	-0.2	91.0		-0.67	-0.54
7	-23.55	-0.06	0.02	-22.87	0.2	-0.4	90.3	-12.48	-0.15	-22.96	-1.4	-0.2	90.8		-0.68	-0.59
8	-23.70	-0.06	0.04	-23.01	0.2	-0.1	90.3	-12.48	-0.14	-23.11	-0.9	0.4	91.2		-0.69	-0.59
9	-23.85	-0.06	0.04	-23.16	0.7	0.0	90.3	-12.47	-0.13	-23.25	-0.9	0.4	91.3		-0.70	-0.60
10	-24.00	-0.07	0.09	-23.32	0.0	-0.5	90.3	-12.50	-0.08	-23.44	-1.2	-0.4	90.9		-0.68	-0.56
11	-24.15	-0.06	0.12	-23.46	0.3	-0.4	90.3	-12.50	-0.06	-23.59	-1.3	-0.4	90.9		-0.69	-0.56
12	-24.30	-0.07	0.11	-23.62	0.0	-0.7	90.3	-12.47	-0.05	-23.70	-1.1	-0.3	90.8		-0.68	-0.60
13	-24.45	-0.07	0.03	-23.76	0.1	-0.4	90.3	-12.49	-0.15	-23.84	-1.2	-0.4	90.8		-0.70	-0.61
14	-24.60	-0.07	0.06	-23.91	-0.1	-0.3	90.3	-12.49	-0.12	-24.01	-1.1	-0.3	90.9		-0.69	-0.59
15	-24.75	-0.08	0.04	-24.05	-0.7	-0.4	90.3	-12.43	-0.10	-24.08	-0.1	0.6	91.2		-0.70	-0.67
16	-24.90	-0.08	0.08	-24.21	-0.8	-0.7	90.4	-12.45	-0.07	-24.25	-0.2	-0.6	91.3		-0.69	-0.65
17	-25.05	-0.08	0.06	-24.34	-0.8	-0.4	90.4								-0.71	
	Max - Min	0.04	0.11		1.60	0.70	0.10	0.07	0.12		1.40	1.20	0.50	0.00	-0.71	-0.67
	Sd	0.01	0.03		0.45	0.18	0.03	0.02	0.04		0.42	0.36	0.18	#DIV/0!	-0.63	-0.48
														Max - Min	0.08	0.19
														Mean	-0.67	-0.57
NOTES	Problem acquiring label 2 occasionaly, esp. @12.													Sd	0.024	0.052
	Failed to acquire label 2 @ 17															

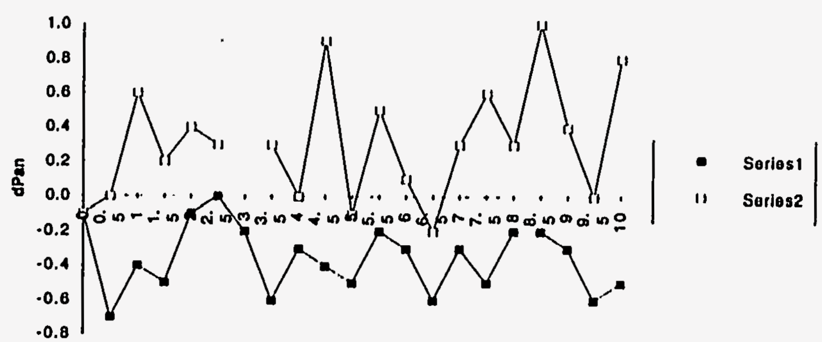
Sample #	Set Pt. Z	Label 1 X	Y	Z	X*	Y*	Z*	Label 2 X	Y	Z	X*	Y*	Z*		Label 1 dZ	Label 2 dZ
Z accuracy - experiment #2				94/12/5												
0	-27.5	-0.02	0.09	-26.74	-0.5	0.0	90.4	-12.39	-0.09	-26.77	-0.2	0.8	91.4		-0.76	-0.73
1	-26.5	-0.03	0.09	-25.76	0.1	-0.2	90.4	-12.46	-0.11	-25.88	-1.2	-0.7	90.7		-0.74	-0.62
2	-25.5	-0.06	0.09	-24.82	-1.5	-0.6	90.4	-12.42	-0.07	-24.87	-0.2	0.6	91.3		-0.68	-0.63
3	-24.5	-0.06	0.08	-23.81	-0.3	-0.4	90.4	-12.46	-0.09	-23.91	-1.0	0.0	91.0		-0.69	-0.59
4	-23.5	-0.06	0.05	-22.81	0.0	-0.1	90.3	-12.46	-0.13	-22.96	-0.9	0.3	91.2		-0.69	-0.54
5	-22.5	-0.07	0.04	-21.90	-1.0	-0.4	90.4	-12.46	-0.14	-22.06	-1.6	-0.1	90.9		-0.60	-0.44
6	-21.5	-0.07	0.00	-20.91	-0.8	-0.3	90.4	-12.48	-0.16	-21.10	-1.8	0.2	91.2		-0.59	-0.40
	Max - Min	0.05	0.09		1.60	0.60	0.10	0.09	0.09		1.60	1.50	0.70	Min	-0.76	-0.73
	Sd	0.02	0.03		0.57	0.20	0.04	0.03	0.03		0.62	0.49	0.24	Max	-0.59	-0.40
														Max - Min	0.17	0.33
														Mean	-0.66	-0.56
														Sd	0.06	0.11





Pan accuracy - experiment #1				94/12/3												
Set Pt.	Z	22.5														
Sample #	Set Pt. Drum angl	Label 1 X	Y	Z	X°	Y°	Z°	Label 2 X	Y	Z	X°	Y°	Z°		Label 1 dPan	Label 2 dPan
0	0	-0.05	0.04	-21.87	-0.1	-0.1	90.3	-12.49	-0.13	-22.03	-1.6	-0.1	90.9		-0 1	-0.1
1	0.5	-0.05	0.00	-21.88	-0.4	-1.2	90.3	-12.47	-0.15	-22.00	-1.4	-0.5	91.0		-0.7	0 0
2	1	-0.07	0.01	-21.88	-0.2	-1.4	90.1	-12.48	-0.01	-22.01	-1.1	-0.4	91 1		-0.4	0.6
3	1.5	-0.07	0.17	-21.88	-0.5	-2.0	90.2	-12.48	0.06	-22.01	-1.4	-1.3	90.8		-0.5	0.2
4	2	-0.07	0.12	-21.88	-0.2	-2.1	90.1	-12.48	0.01	-22.01	-1.4	-1 6	90.9		-0 1	0.4
5	2.5	-0.05	0.05	-21.86	-0.4	-2.5	90.4	-12.47	-0.12	-22.00	-1.4	-2.2	91.0		0.0	0.3
6	3	-0.05	0.03	-21.84	0.0	-3.2	90.3								-0.2	
7	3.5	-0.05	0.01	-21.85	0.1	-4.1	90.4	-12.49	-0.15	-22.02	-1.4	-3.2	91 2		-0.6	0 3
8	4	-0.04	0.10	-21.81	0.8	-4.3	90.3	-12.50	-0.08	-21.98	-1.8	-4.0	91.0		-0.3	0.0
9	4.5	-0.05	0.04	-21.84	-0.2	-4.9	90.4	-12.48	-0.11	-22.00	-1.0	-3.6	91.5		-0.4	0.9
10	5	-0.05	0.04	-21.86	-0.1	-5.5	90.4	-12.50	-0.13	-22.02	-1.9	-5.1	91.0		-0.5	-0.1
11	5.5	-0.07	0.11	-21.85	-0.5	-5.7	90.2	-12.47	-0.19	-22.04	-1.0	-5.0	91.3		-0.2	0.5
12	6	-0.05	0.04	-21.85	0.2	-6.3	90.3	-12.49	-0.13	-22.01	-2.0	-5.9	91.0		-0.3	0.1
13	6.5	-0.05	0.02	-21.85	-0.5	-7.1	90.4	-12.50	-0.16	-22.01	-2.0	-6.7	90.9		-0.6	-0.2
14	7	-0.06	0.07	-21.86	-0.5	-7.3	90.4	-12.49	-0.10	-22.06	-1.6	-6.7	91.1		-0.3	0.3
15	7.5	-0.05	0.03	-21.87	-0.1	-8.0	90.3	-12.49	-0.13	-22.01	-1.0	-6.9	91.4		-0.5	0.6
16	8	-0.06	0.07	-21.85	-0.5	-8.2	90.4	-12.51	-0.10	-22.04	-1.6	-7.7	91.1		-0.2	0.3
17	8.5	-0.05	0.07	-21.82	-0.1	-8.7	90.4	-12.50	-0.09	-22.02	-1.0	-7.5	91.4		-0.2	1.0
18	9	-0.05	0.07	-21.81	-0.1	-9.3	90.4	-12.50	-0.09	-22.04	-1.8	-8.6	91.1		-0.3	0.4
19	9.5	-0.06	0.06	-21.86	-0.8	-10.1	90.4	-12.51	-0.10	-22.07	-1.8	-9.5	91.0		-0.6	0.0
20	10	-0.06	0.04	-21.82	-1.0	-10.5	90.4	-12.49	-0.11	-22.03	-1.3	-9.2	91.3		-0.5	0.8
	Max - Min	0.03	0.17	0.07	1.80		0.30	0.04	0.25	0.09	1.00		0.70	Min	-0.7	-0.2
	Sd	0.01	0.04	0.02	0.38		0.10	0.01	0.06	0.02	0.34		0.19	Max	0.0	1.0
														Max - Min	0.7	1.2
														Mean	-0.4	0.3
														Sd	0.19	0.34

NOTES: Label 2 is frequently lost (esp. the left face which is furthest away)



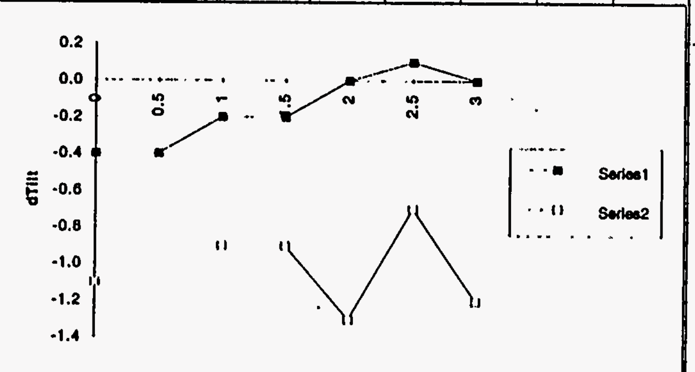
Tilt accuracy - experiment #1				94/12/3															
Set Pt.	Z	22.5																	
Sample #	Set Pt. Tilt	X	dZ	Label 1 X	Y	Z	X°	Y°	Z°	Label 2 X	Y	Z	X°	Y°	Z°			Label 1 dTilt	Label 2 dTilt
0	0	-0.44	22.5	-0.07	-0.01	-21.86	-0.4	-0.2	90.3	-12.48	-0.15	-22.00	-1.1	0.5	91.2			-0.4	-1.1
1	0.5	-0.244	22.5	-0.07	0.01	-21.86	-0.9	-0.3	90.4	-12.48	-0.15	-22.12	*	*	*			-0.4	
2	1	-0.047	22.5	-0.08	0.01	-21.86	-1.2	-0.3	90.3	-12.52	-0.14	-22.20	-1.9	0.6	91.3			-0.2	-0.9
3	1.5	0.149	22.5	-0.06	0.01	-21.88	-1.7	-0.3	90.3	-12.46	-0.15	-22.30	-2.4	0.5	91.3			-0.2	-0.9
4	2	0.346	22.5	-0.09	0.02	-21.88	-2.0	-0.3	90.3	-12.50	-0.15	-22.45	-3.3	0.5	90.9			0.0	-1.3
5	2.5	0.543	22.499	-0.07	0.02	-21.91	-2.4	-0.2	90.3	-12.48	-0.13	-22.52	-3.2	0.6	91.2			0.1	-0.7
6	3	0.741	22.498	-0.07	0.02	-21.91	-3.0	-0.3	90.3	-12.47	-0.14	-22.67	-4.2	-0.1	90.9			0.0	-1.2
			Max - Min	0.03	0.03	0.05		0.10	0.10	0.06	0.02	0.67		0.70	0.40		Min	-0.4	-1.3
			Sd	0.01	0.01	0.02		0.05	0.04	0.02	0.01	0.24		0.27	0.19		Max	0.1	-0.7
																	Max - Min	0.5	0.6
																	Mean	-0.2	-1.0
																	Sd	0.2	0.2

NOTES: * = unstable result

X angle varying from -1.8 - -3.6

Y angle varying from 0.7 to 1.0

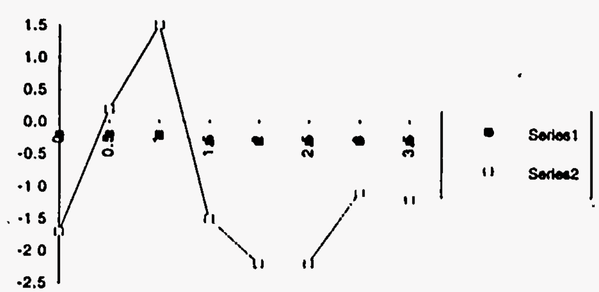
Z angle varying from 91.1 to 91.3



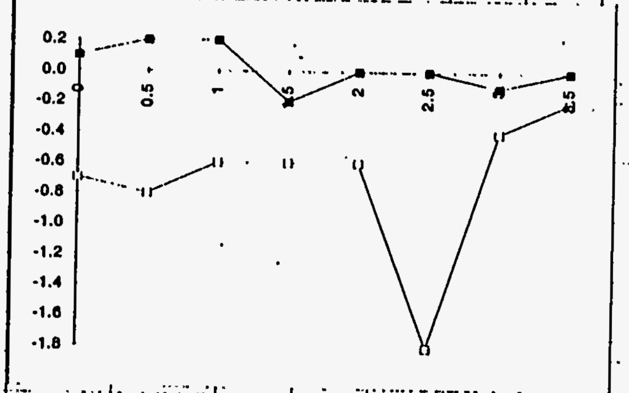
Tilt accuracy - experiment #2

Set Pt. | Z | 22.5

Sample #	Set Pt. Tilt	Label 1 X	Y	Z	X°	Y°	Z°	Label 2 X	Y	Z	X°	Y°	Z°	Notes		Label 1 dTilt	Label 2 dTilt
0	0	0.00	0.03	-22.10	-0.2	0.3	90.9	-12.32	-0.17	-22.06	-1.7	1.6	91.5			-0.2	-1.7
1	0.5	0.01	0.04	-22.10	-0.7	0.3	90.9	-12.30	-0.18	-22.14	-0.3	0.8	91.4			-0.2	0.2
2	1	-0.01	0.04	-22.10	-1.2	0.3	90.9	-12.68	-0.29	-23.17	0.5	3.6	91.6	1		-0.2	1.5
3	1.5	-0.01	0.04	-22.10	-1.8	0.3	90.9	-12.32	-0.16	-22.37	-3.0	1.5	91.4			-0.3	-1.5
4	2	-0.01	0.04	-22.11	-2.3	0.3	90.8	-12.31	-0.17	-22.51	-4.2	1.1	91.4			-0.3	-2.2
5	2.5	-0.03	0.04	-22.11	-2.8	0.3	90.8	-12.33	-0.17	-22.63	-4.7	1.0	91.4	2		-0.3	-2.2
6	3	-0.04	0.03	-22.13	-3.3	0.3	90.8	-12.32	-0.16	-22.68	-4.1	1.6	91.4	2		-0.3	-1.1
7	3.5	-0.05	0.03	-22.13	-3.8	0.3	90.8	-12.34	-0.17	-22.80	-4.7	1.5	91 4	2		-0.3	-1.2
	Max - Min	0.06	0.01	0.03		0.00	0.10	0.38	0.13	1.11		2.80	0.20		Min	-0.3	-2.2
	Sd	0.02	0.01	0.01		0.00	0.05	0.13	0.04	0.36		0.87	0.07		Max	-0.2	1.5
															Max - Min	0.1	3.7
	NOTES:	1	Only left face detected												Mean	-0.3	-1.0
		2	Required several frames to acquire both faces												Sd	0.1	1.3



Tilt accuracy - experiment #3			3.2° face														
Set Pt.	Z	22.5															
Sample #	Set Pt. Tilt	Label 1 X	Y	Z	X°	Y°	Z°	Label 2 X	Y	Z	X°	Y°	Z°	Notes		Label 1 dTilt	Label 2 dTilt
0	0	0.00	-0.02	-21.86	0.1	0.0	90.9	-12.44	-0.26	-21.96	-0.7	0.4	91.6			0.1	-0.7
1	0.5	-0.02	-0.01	-21.86	-0.3	0.0	90.9	-12.48	-0.25	-22.07	-1.3	0.3	91.5	1		0.2	-0.8
2	1	-0.03	-0.01	-21.85	-0.8	0.0	90.9	-12.48	-0.24	-22.16	-1.6	0.3	91.5			0.2	-0.6
3	1.5	-0.03	-0.01	-21.85	-1.7	0.0	90.9	-12.48	-0.25	-22.26	-2.1	0.3	91.5	1		-0.2	-0.6
4	2	-0.05	-0.01	-21.86	-2.0	0.0	90.9	-12.50	-0.25	-22.38	-2.6	0.1	91.5	1		0.0	-0.6
5	2.5	-0.06	-0.01	-21.87	-2.5	0.1	90.9	-12.49	-0.22	-22.46	-4.3	1.3	91.7			0.0	-1.8
6	3	-0.05	-0.01	-21.88	-3.1	0.0	90.9	-12.48	-0.23	-22.58	-3.4	0.2	91.5			-0.1	-0.4
7	3.5	-0.06	-0.01	-21.89	-3.5	0.1	90.9	-12.47	-0.23	-22.68	-3.7	0.4	91.5			0.0	-0.2
	Max - Min	0.06	0.01	0.03	N/A	0.10	0.00	0.06	0.04	N/A	N/A	1.20	0.20		Min	-0.2	-1.8
	Sd	0.02	0.00	0.01	N/A	0.05	0.00	0.02	0.01	N/A	N/A	0.37	0.07		Max	0.2	-0.2
	NOTES:	1. Right face of label 2 difficult to detect													Max - Min	0.4	1.6
															Mean	0.0	-0.7
															Sd	0.1	0.5



PHASE 1 TOPICAL REPORT

ATTACHMENT 1.4

Automated Baseline Change Detection

Task 1 Summary Results

ABCD Performance Criteria

(Presented on the next 2 pages.)

ABCD PERFORMANCE CRITERIA

The following parameters and values form a consistent set of Task 1 Performance Criteria, as determined by the optics model and calibration tools developed for ABCD.

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 treshold 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

PHASE 1 TOPICAL REPORT

ATTACHMENT 2

Automated Baseline Change Detection

Task 2 Summary Results

PHASE 1 TOPICAL REPORT

ATTACHMENT 2

Automated Baseline Change Detection

Task 2 Summary Results

Change-Detection Application System Verification Experimental Results

(Presented in the next 10 pages in original format.)

STATUS REPORT ATTACHMENT 1

FOR THE MONTH OF MAY 1995
June 15, 1995

Automated Baseline Change Detection

Work Performed Under Contract:
DE-AR21-94MC31191

Change-Detection Application System Verification Experimental Results

A1.1 Introduction

This attachment presents the experimental results of Phase 1 Task 2, Change-Detection Application System Verification. The primary objective of Task 2 was to verify that the performance criteria established in Task 1 are met. The performance criteria are presented in section A1.2 and the experimental design and results are presented in section A1.3.

The verification experiments for Task 2 were designed to find reliable limits of the Baseline Change Detection (BCD) system to find true-positive changes according to Task 1 criteria. In searching for limits in this fashion, cases beyond the limits are found. These are errors if the performance criteria are not satisfied. There are two types of such errors, false-negative changes (missed changes) and false-positive changes (reported changes that do not really exist).

Generally, the performance criteria were verified. However, lighting uniformity, camera saturation, specular reflections, and the wide dynamic range of black barrels with white labels were all more difficult to handle than anticipated.

Cases where all these factors are simultaneously at their independent limits tend to yield false-negatives. For example, small, dark gray on black changes far from the center of the barrel (low and/or at large azimuthal angles) are often not detected. But if only one of these factors is at its limit, such as the azimuthal angle from the center, then the criteria are satisfied. More uniform lighting with more dynamic control of intensity are being considered to reduce the false-negative rate.

In addition to false-negatives, other problems were experienced with false-positives. Usually these are associated with high-gradient changes in image intensity, such as in regions of specular reflection (mirror-like reflection). Exclusion masks for specular-reflection regions and improved registration of inspection images to baseline images will decrease the false-positive rates. These are being actively pursued.

A1.2 Task 1 Performance Criteria Summary

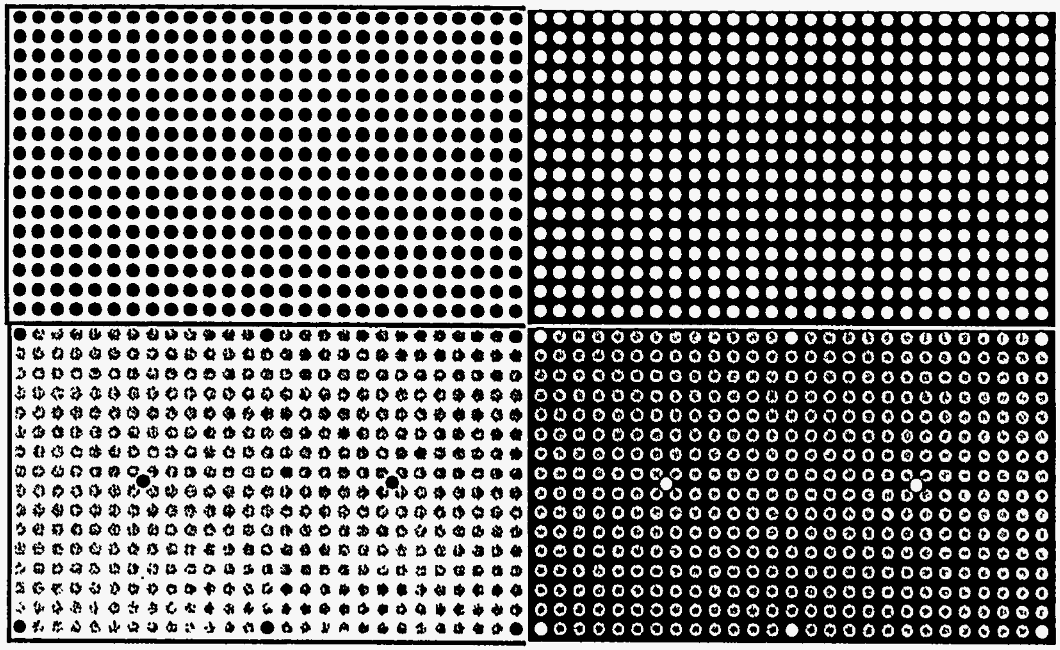
The Task 1 performance criteria are summarized below and were reported in the ABCD December 1994 Status Report. The criteria shown are a consistent set for a 4.3 mm focal-length lens in the standard pose. If and when another lens is used, the pin-hole camera model developed in Task 1 will be used to establish another camera-dependent set of criteria. In all cases, the barrel-area per pixel is taken as constant and empirically determined performance criteria are otherwise unchanged.

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

A1.3 Task 2 Verification

The following figures present the test patterns, sample images, and the change-detection results. Each of the nine figures has a fully descriptive caption. The figures are in the following order:



Variables:

- Defect Size
- Defect Spacing
- White on Black
- Black on White
- 20 % Grey on White
- 80 % Grey on Black

FIGURE 1. CHANGE-DETECTION TEST PATTERNS. In order to test the Automated Baseline Change Detection sensor system, test patterns were constructed that could be applied to the waste barrels in the laboratory. These test patterns were designed to validate the performance of the sensor system relative to the change detection criteria developed in Task 1. The most important of these were the size and contrast change limits for a detected change on the barrel. To test the extremes of these criteria, test patterns of varying defect size, spacing, and gray scale were produced. The gray scale variation was limited to either white defects on a black background, 80% gray scale defects on a black background, black defects on a white back ground, and 20% gray scale defects on a white background, as these were the limiting cases for the change detection criteria. Fiducial spots that gave full black/white gray scale contrast were placed on each pattern.

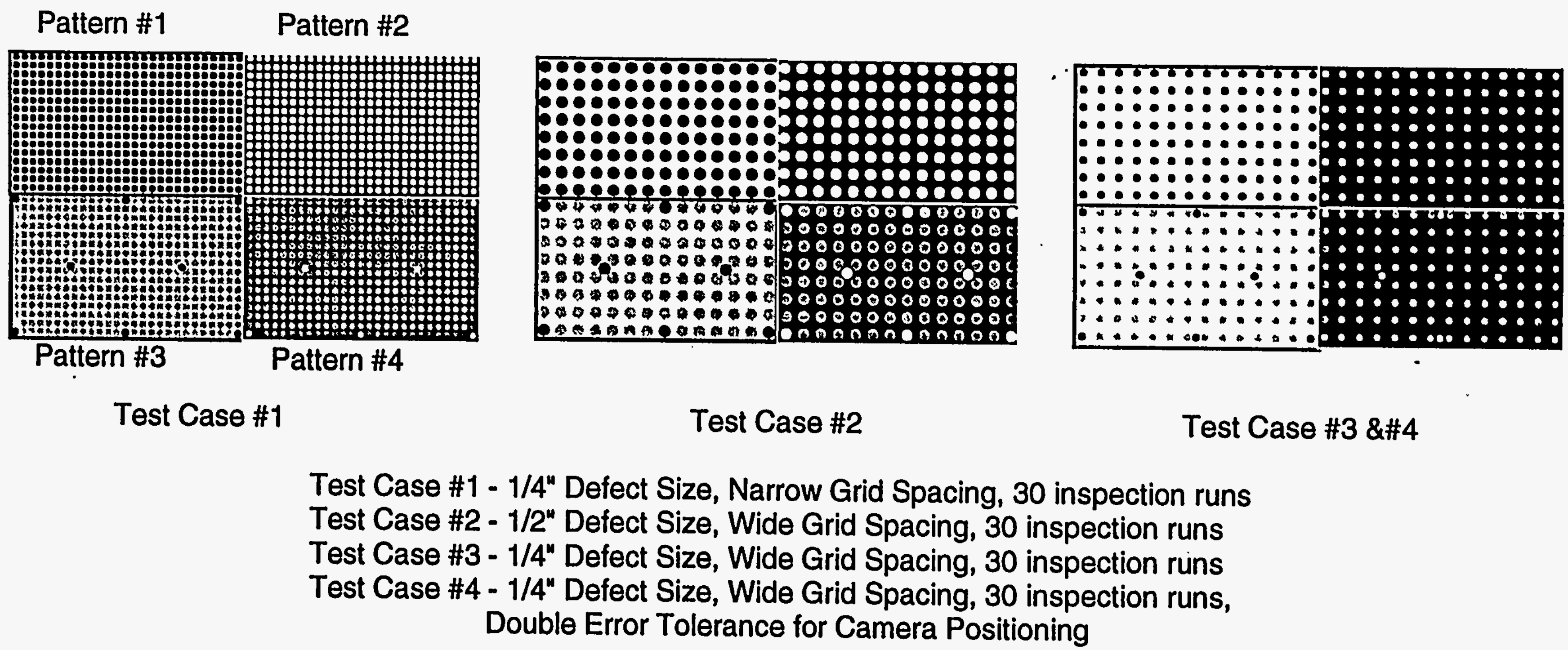


FIGURE 2. EXPERIMENTAL TEST CASES. A subset of test patterns was chosen to perform four sets of experiments. For each of these four test cases, 30 change detection runs were made with each set of test patterns. Each change detection run consisted of recentering the BCD sensor to the desired standoff location from the Eagle Eye marker label, acquiring an inspection image, acquiring an ambient image, and then performing the ambient subtraction, intensity normalization, image registration, and baseline image subtraction to detect the changes introduced by the test patterns. The four test cases can be categorized as: 1) 1/4" Defects with Narrow Spacing, 2) 1/2" Defects with Wide Spacing, 3) 1/4" Defects with Wide Spacing, and 4) 1/4" Defects with Wide Spacing and Higher Camera Positioning Error. The fourth test case used the same set of test patterns as the third test case, but was added to examine the effect of camera positioning error on the change detection performance.

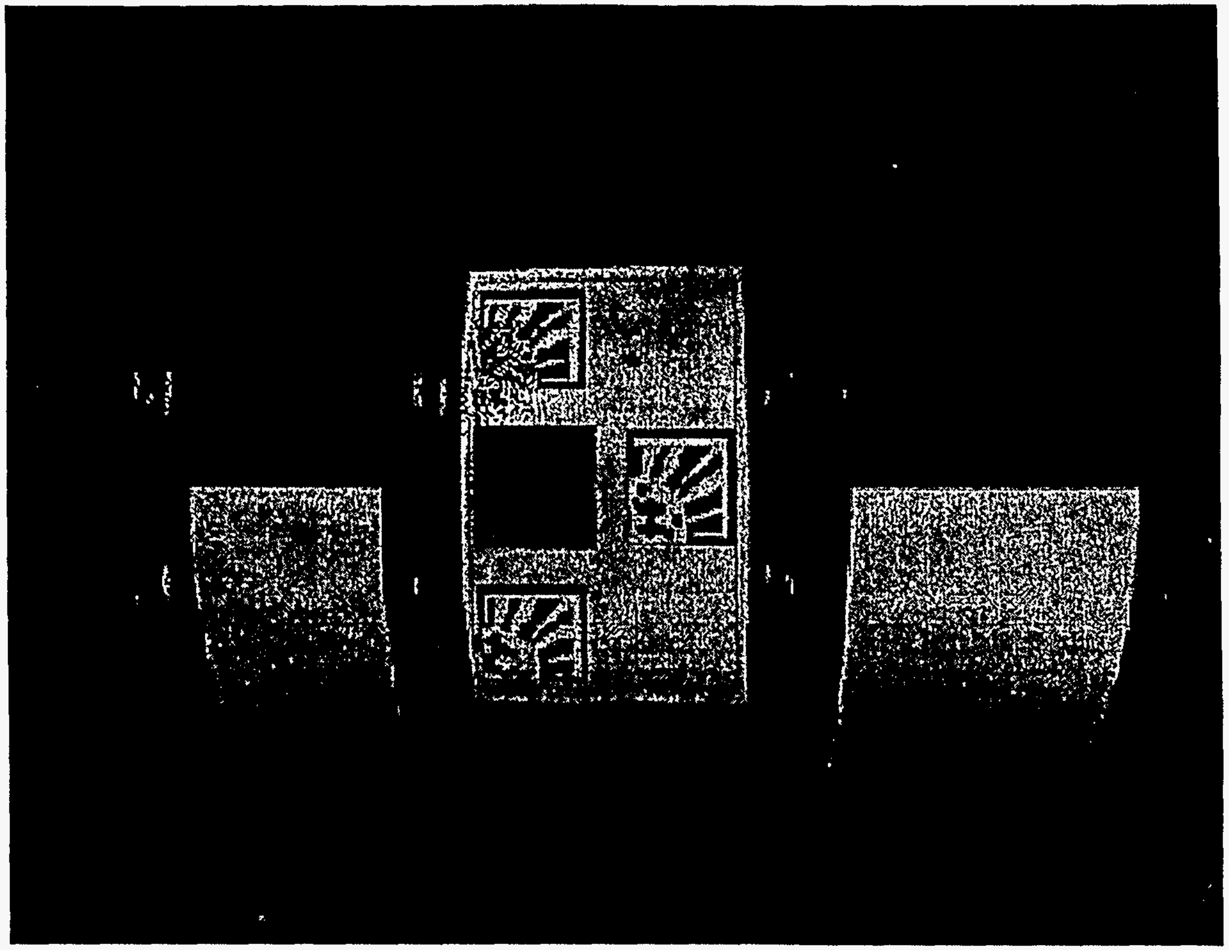


FIGURE 3. BASELINE IMAGE An example baseline stored image of a waste barrel is shown. The barrel top is at the image left. This image is the result of an image subtraction between an image of the barrel illuminated by both the sensor system lighting and the ambient lighting, and an image illuminated solely by ambient lighting, resulting in a black background. A three face Eagle Eye marker is visible in the center of the barrel, as are the four background areas to which the change detection test patterns are affixed in each quadrant of the barrel.

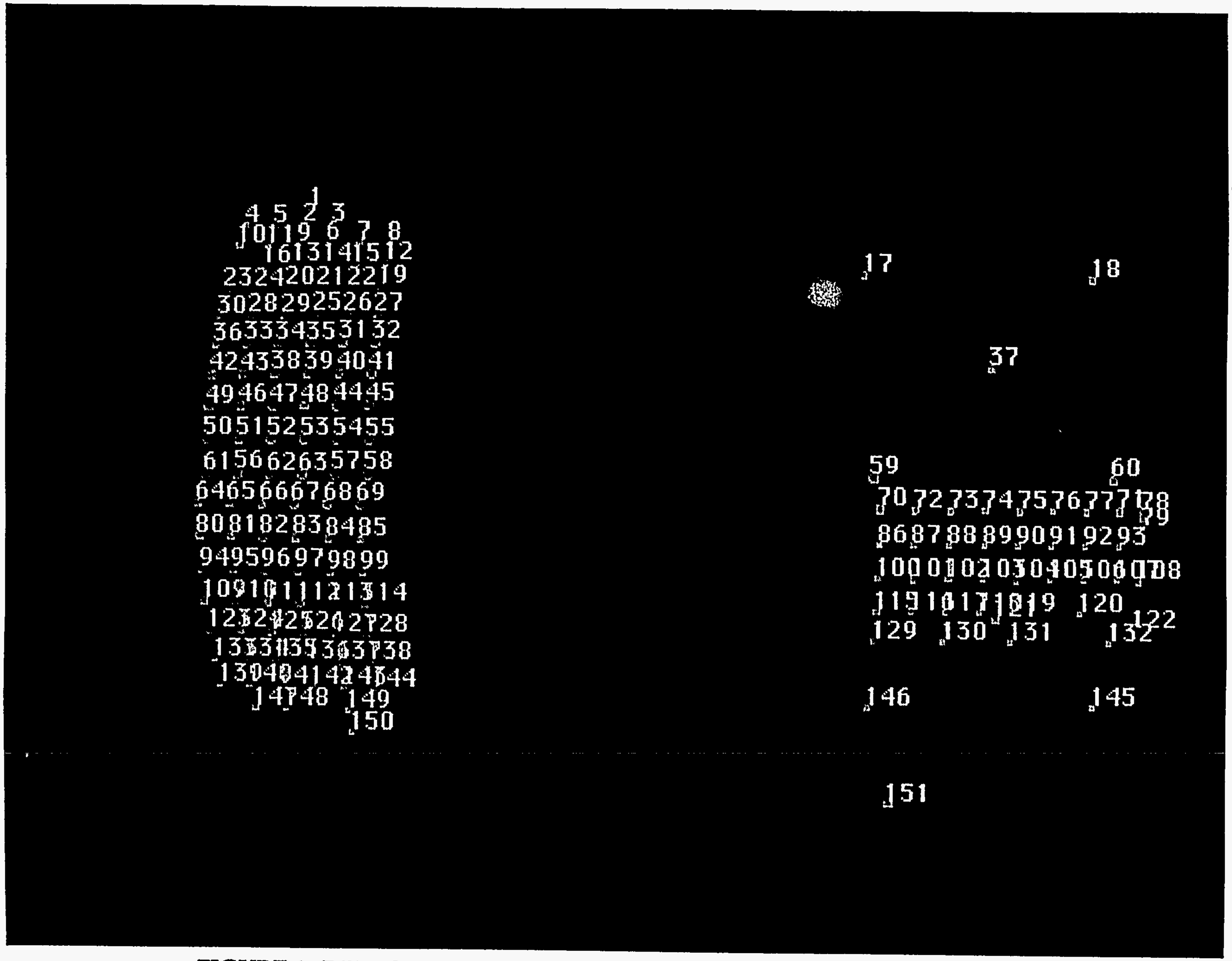


FIGURE 4. DETECTED CHANGES EXAMPLE. SEE CAPTION NEXT PAGE.

FIGURE 4. DETECTED CHANGES EXAMPLE IMAGE. (SEE FIGURE ON PRECEEDING PAGE). An example subtracted difference image is presented with detected changes numbered. Note the complete cancellation of the Eagle Eye marker in the subtracted image. Also note that the best performance for change detection off the barrel centerline was for the test pattern with white defects on a black background (upper right quadrant of the barrel), while the worst performance was for the 80% gray scale defects on a black background (lower right quadrant of the barrel). For that test pattern only the fiducial markings are visible in the difference image, at each corner and in the center. Also note the false positive changes introduced in the lower left quadrant due to improper alignment of the test pattern with its background.

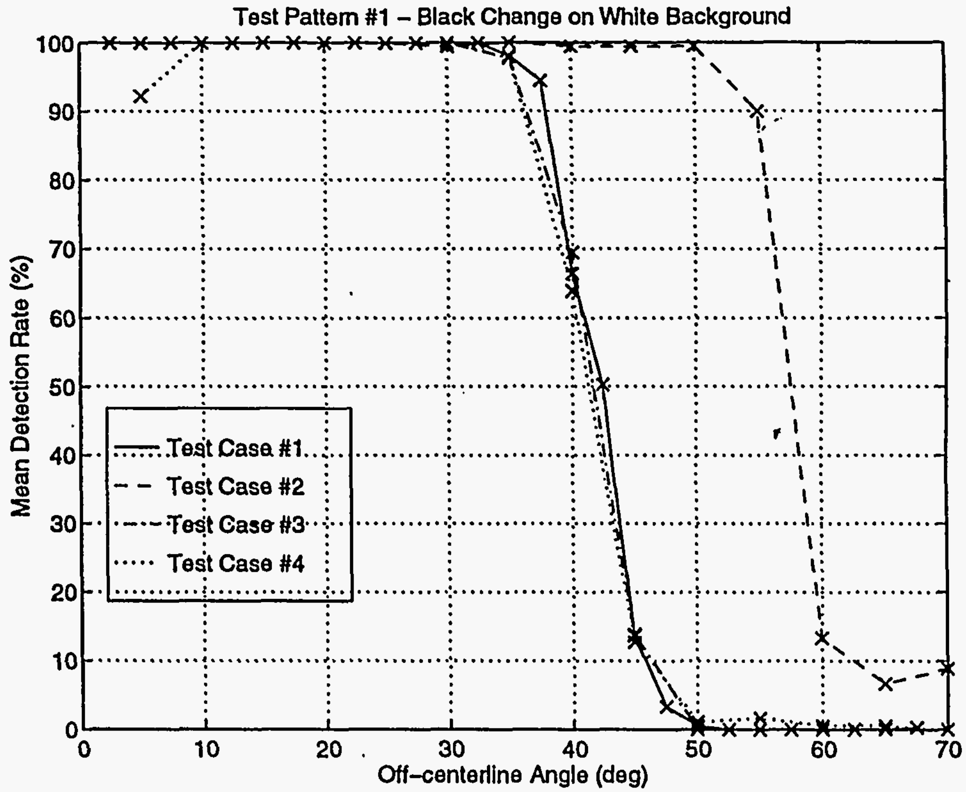


FIGURE 5. MEAN DETECTION RATES FOR TEST PATTERN #1. For test pattern 1, the black defects on a white background (upper left quadrant of the test barrel), the average true positive detection rate as a function of angular distance from the barrel centerline can be plotted. This was done by taking the mean of the detection rate per barrel inspection for each column of the test pattern over the 30 test runs for each of the four test cases. Four curves are plotted, one for each test case. The false negative rate is just the complement percentages to these curves. The change detection criteria set up in Task 1 specified that the system be able to find the 1/4" changes if they were within +/- 40° of the barrel centerline, and the curves for test cases 1,3, and 4 (which have 1/4" defects) show that this requirement is nearly met. 100% mean detection rate is achieved out for +/- 35°, with detection rate dropping to 65-70% at +/- 40°. Note that for testcase 2, where the defect size was increased to 1/2", the detection rate easily meets the criteria, with 100% detection rate out to +/- 50°. It is also interesting that the increase in camera position error tolerance for testcase 4 had little effect on the detection rate. This was probably due to the fact that while the error tolerance was increased, the actual camera positioning error was unchanged in testcase 4.

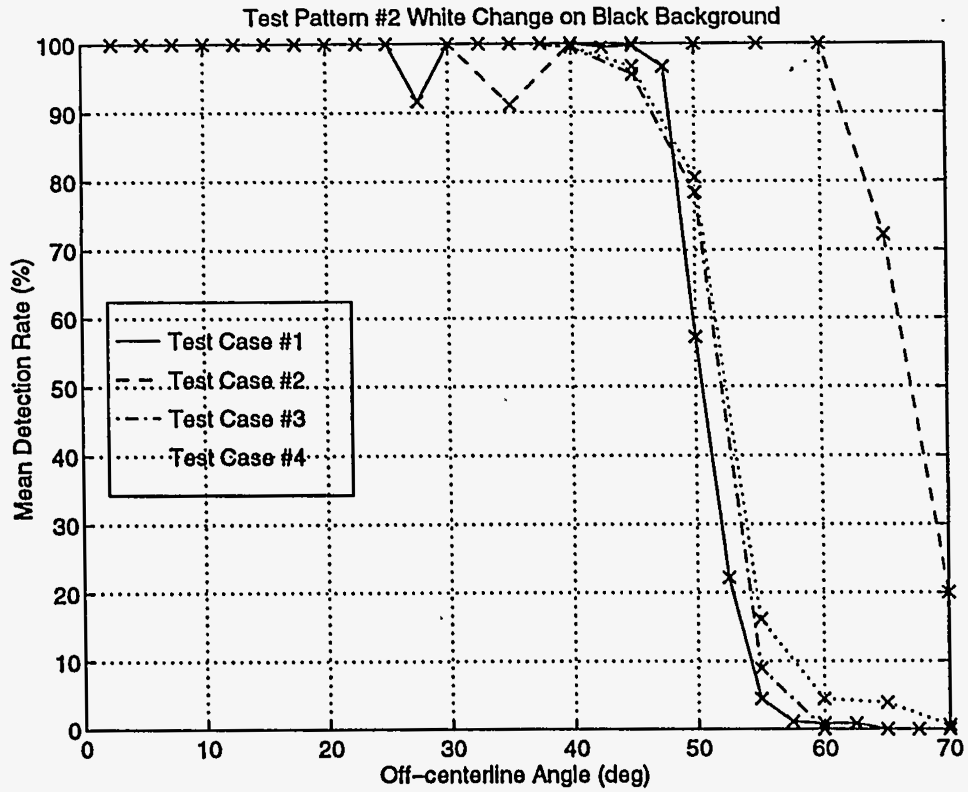


FIGURE 6. MEAN DETECTION RATES FOR TEST PATTERN #2. For test pattern 2, the white defects on a black background (barrel upper right quadrant), the change detection criteria set up in Task 1 of being able to find the 1/4" changes if they were within +/- 40° of the barrel centerline is met. 100% mean detection rate is achieved out for +/- 40° for all four test cases, with detection rate dropping to 55-80% at +/- 50°. Note that again for testcase 2, where the defect size was increased to 1/2", the detection range was pushed out farther on the barrel, with 100% detection rate out to +/- 60°.

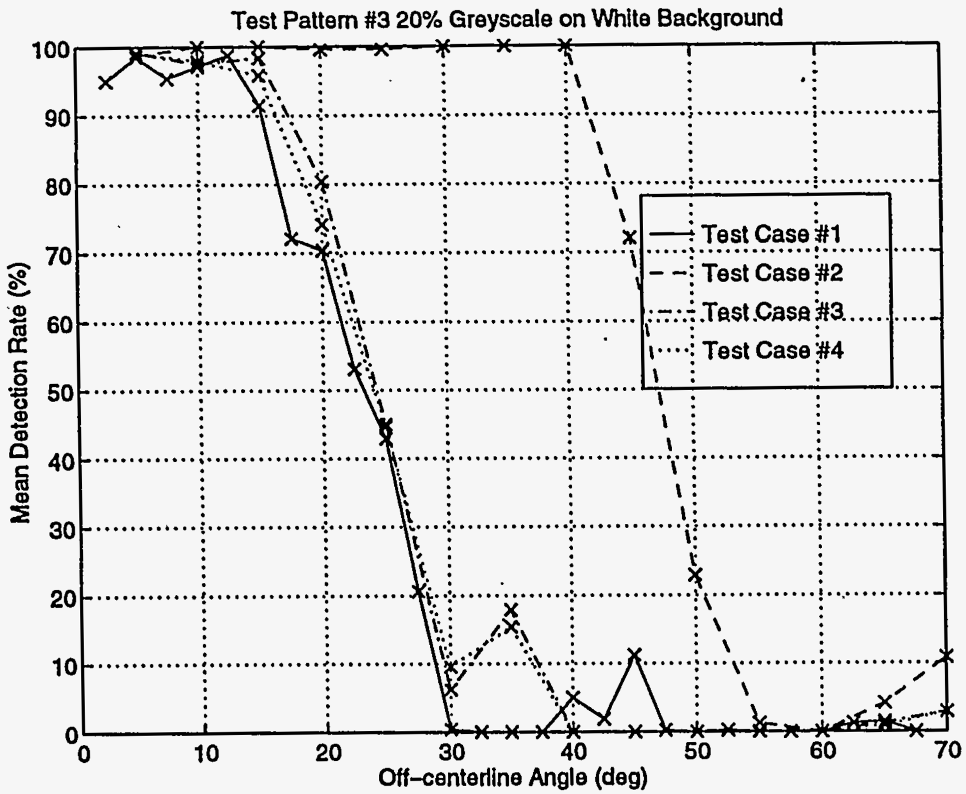


FIGURE 7. MEAN DETECTION RATES FOR TEST PATTERN #3. For test pattern 3, the 20% gray scale defects on a white background (barrel lower left quadrant), the change detection criteria are met for testcase 2 because of the increase in defect size to 1/2". 100% mean detection rate is achieved out to +/- 40°, with detection rate dropping to 23% at +/- 50°. For testcases 1,3, and 4, where the defect size was 1/4", the detection rate was at best 95-100% only out to +/- 15° from the barrel centerline. This result is not surprising, as finding barrel defects with this small gray scale change and small size is challenging and very illumination dependent. During these experiments, it was found that a trade off had to be made between illumination necessary to bring out the contrast difference necessary for successful change detection and that which is necessary for successful barrel marker tracking.

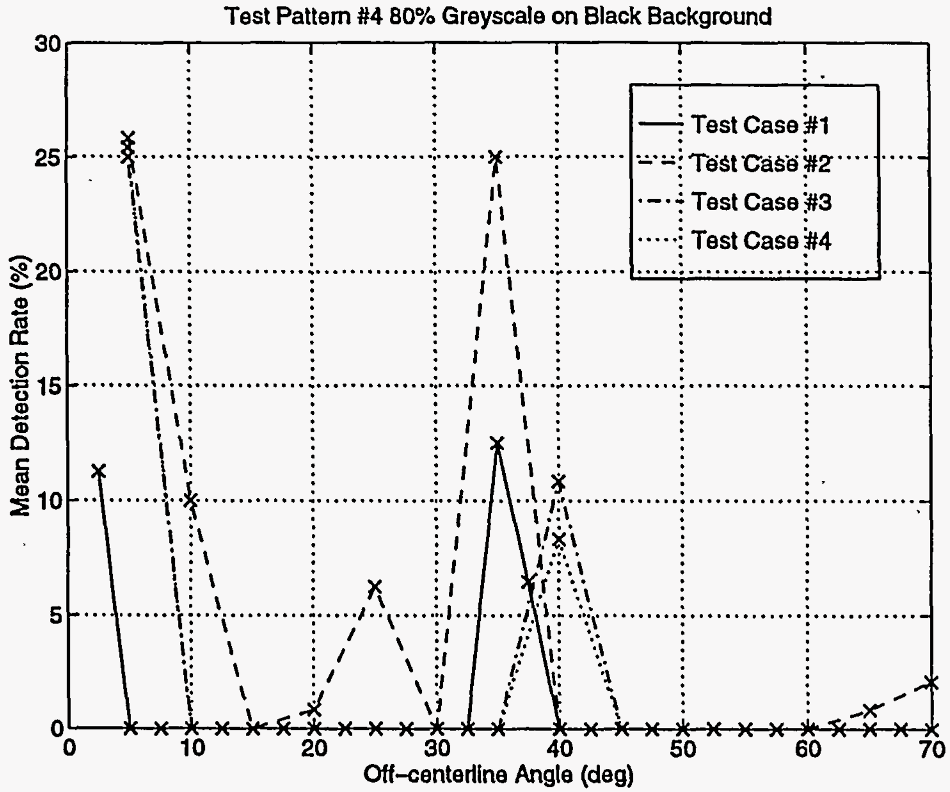


FIGURE 8. MEAN DETECTION RATES FOR TEST PATTERN #4. For test pattern 4, the 80% gray scale defects on a black background (lower right quadrant of the test barrel), the average true positive detection rate was effectively nil for all four testcases. It was less than 10% for all angles off barrel centerline for testcases 1,3, and 4, and never greater than 25% for testcase 2 with the larger, 1/2", defect size. This inability to detect this low gray scale difference change, like test pattern 3, was also illumination dependent. It was found during the experiments, that some changes could be detected on test pattern 4 if the illumination was increased to give sufficient contrast differences to the defects, but that this tended to saturate the image in other areas. In practice, two ways of handling this problem might be; 1) variable illumination for tracking and change detection, and 2) vary illumination based on overall average gray scale value for barrel, i.e., vary illumination to look for black spots on white barrels, or black spots on white barrels.

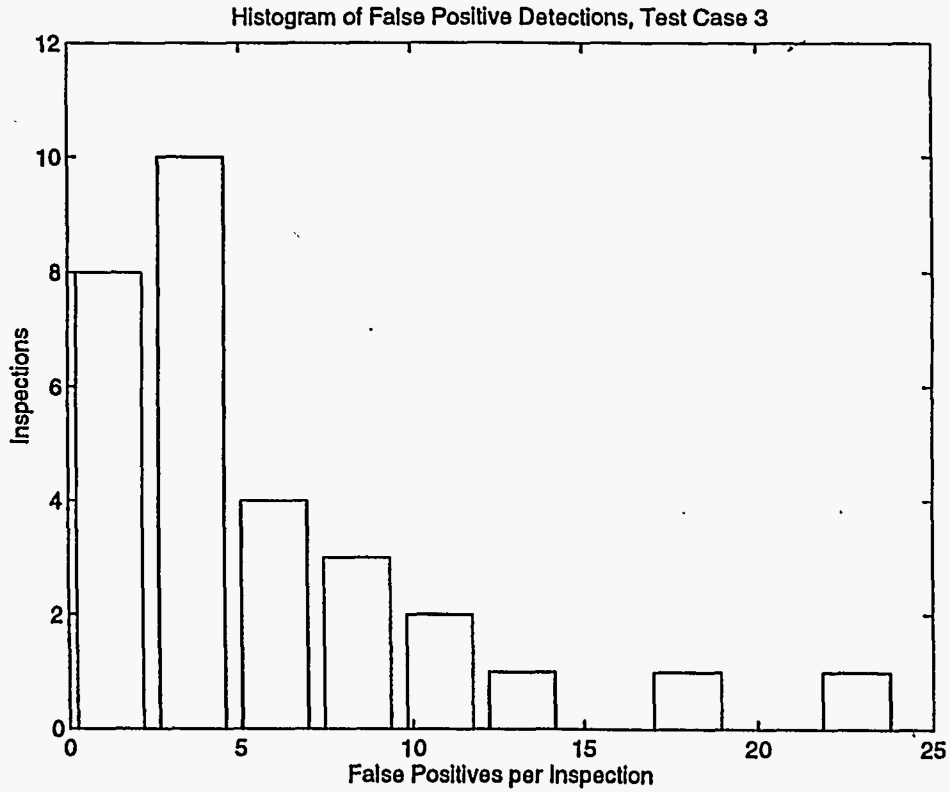


FIGURE 9. FALSE POSITIVE HISTOGRAM. A histogram of the false positive rates for each barrel inspection for testcase 3 is presented. This result for false positive rate reflects a worse case condition where no intelligent masking of known sources of false positive detections (for example those along the edge of the test patterns themselves) is taken advantage of.

PHASE 1 TOPICAL REPORT

ATTACHMENT 3

Automated Baseline Change Detection

Task 3 Summary Results

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Task 3 Summary Results

Change-Detection Deployment System Verification

Contents

3.0 INTRODUCTION

The main goals of Task 3 of the Automated Baseline Change Detection (ABCD) contract were to install the barrel defect detection system on a mobile robotic platform and evaluate the change detection performance on a multiple-barrel array. This array was to be a three pallet tier high stack and at least three stacks wide, similar to actual warehouse conditions, but located in a laboratory setting for this phase of testing. Barrel inspection was to be done by designing and building a fast, high-precision camera-positioning mast to be mounted on an existing LMMS mobile robot. The emphasis was on the change-detection imaging and not the platform, with the later objective of integrating the ABCD system with fieldable mobile platform.

With the merger of Lockheed and Martin Marietta these objectives were modified. A further goal of Task 3 was to integrate the contract efforts of the Intelligent Mobile Sensing System (IMSS) underway at Lockheed Martin Astronautics(LMA) in Denver, CO, with the ABCD contract work being conducted at Lockheed Martin Missiles and Space (LMMS) in Palo Alto, CA, and Kinetic Sciences, Inc., in Vancouver, BC. Task 2 of the ABCD contract had demonstrated successfully using camera registration and image subtraction for barrel defect detection. Under the IMSS contract, the Denver group had constructed a versatile autonomous robotic sensor platform with image analysis capability, and a simulated waste storage facility in their laboratory. Since both contracts had the goal of producing a working mobile inspection system, it was decided to take advantage of the synergy between the two groups and install the ABCD change detection system on the IMSS mobile platform.

Before the final tests could be conducted, preliminary tests and changes were required to adapt ABCD to the IMSS platform. The main issue is with less precise IMSS camera repositioning. Also, in the course of determining DOE requirements in Task 4, it was evident that the range of barrel colors was much larger than expected. This significantly effects the importance of lighting, an issue that was more fully resolved in Phase 2. With the early, and cost-effective integration of ABCD with IMSS, the ABCD system required additional Phase 1 upgrades to account for less precise positioning and more variation in lighting.

Therefore, in this report of Task 3, Change-Detection Deployment System Verification, is organized into two main sections.

- 3.1 ABCD Phase 1 Task 3 Imaging Enhancements
- 3.2 ABCD Phase 1 Task 3 Imaging Experiments
- 3.3 ABCD Phase 1 Task 3 Conclusions

3.1 ABCD Phase 1 Task 3 Imaging Enhancements

In Phase 1, Task 1 the ABCD performance criteria were established. In Task 2 it was verified that the ABCD system could meet these criteria on a single barrel with high statistical reliability. Task 3 was to demonstrate the same capabilities for an array of barrels. The integration with IMSS effectively changed the performance criteria, requiring registration of two images with less precise camera positioning and higher variation in barrel surfaces and lighting. These were know issues, but rather than being addressed in Phase 2, they were addressed in Phase 1, Task 3. This was a highly beneficial turn of events for the DOE and for Lockheed Martin. Rather than developing an intermediate mobile platform, the effort went into early enhancement of the ABCD imaging capabilities.

These developments are discussed in detail in Sections 4.0 and 5.0 of the ABCD Phase 1 Topical Report. For completeness, major portions of those sections are included here. The number in parentheses refer to the source sections.

3.1.1 "Tiling" Image Registration Algorithm (5.18)

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.

3.1.2 Image Processing Consultation (5.19)

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.

3.1.3 Image Registration (5.22)

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.

3.1.4 Enhancements to System Software (5.23)

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.

3.1.5 IMSS Platform Testing (5.24)

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.

3.1.6 Tiling for IMSS (5.25)

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.

3.2 ABCD Phase 1 Task 3 Imaging 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.

3.2.1 Laboratory Setup

There were two main concerns addressed before the integration of the ABCD system with the IMSS could be accomplished. The first was whether the IMSS sensor pod could provide the necessary image data for the change detection, and the second concern was whether the ABCD change detection software could be run on the IMSS laboratory computing platforms.

The IMSS sensor pod cameras were of longer focal length than those used in the ABCD Task 2 tests, and produced a 'four quadrant' view of the inspected barrel rather than a single image. Also, the light levels, produced by the sensor pod were a factor of 4 lower than what was used in the Task 2 tests, and the ability to toggle the lights on and off for ambient light subtraction had to be added. Finally, the IMSS mobile platform had less repositioning accuracy than the fixed based robot manipulator used in Task 2 testing, which would affect the camera registration and image subtraction.

To address these issues, the IMSS sensor pod was brought to the LMMS laboratory in Palo Alto, where a series of change-detection tests were performed. A calibration of the cameras was performed and it was found that by varying the change detection software parameters, successful image subtraction could be performed at the lower light levels and with on the order of 1-2 cm. camera repositioning error.

The second main concern was that the ABCD software could run in the IMSS computing environment. The ABCD control software communicated via a TCP socket interface, and is C source code that could be compiled and run on the IMSS lab workstations. The ABCD image processing software runs on the Apple Power PC platform, and also communicates through a TCP interface. A Power PC was available in the IMSS lab to run the image processing software.

A description of the hardware and software used during the Task 3 testing follows.

3.2.1.1 Hardware

The equipment used during the inspection tests consisted of the IMSS mobile robot platform, its cameras, lenses and lighting, the computer platforms, and the simulated waste storage facility set up in the IMSS laboratory.

3.2.1.1.1 IMSS -

The Intelligent Mobile Sensor System robotic platform is shown in Figure 1. It consists of a mobile base and a mast that supports three sensor pods, arranged vertically to correspond to the heights of a three tier stack of 55 gallon barrels on pallets. The mobile base has all the onboard sensing and computing necessary to center the vehicle on a stack of barrels in a warehouse aisle, and the mast can position the sensor pods at a desired standoff distance from the barrels. The sensor pods have a pitch axis that can point the cameras at the upper or lower quadrants of the barrel. During Task 3 testing, only 2 of the IMSS sensor pods were functional; the upper and lower pods. Because of this, the test array of barrels for inspection included only top and bottom tier barrels, however this did not affect the generality of the test results.

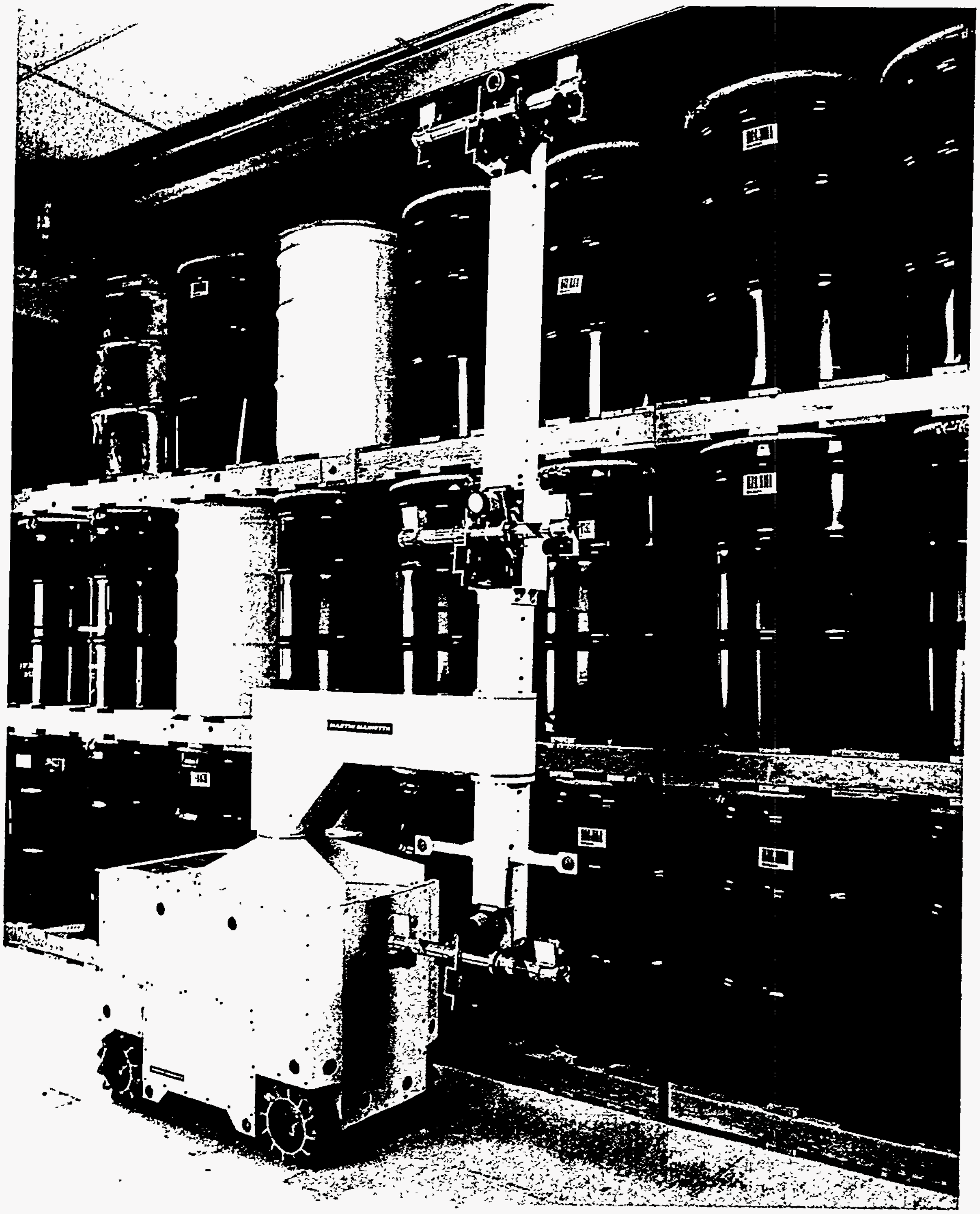


Figure 1. The IMSS (Intelligent Mobile Sensor System) and warehouse-simulation facility was used for ABCD (Automated Baseline Change Detection) Phase 1 experiments.

3.2.1.1.2 Barrel Array -

The array of barrels chosen for testing included the top and bottom rows of one aisle in the simulated warehouse. This consisted of 10 barrels of varying color, surface texture, ambient lighting, and reflectivity. (See Figures 1&3) The barrels were on pallets with varying overhang and position offset from the barrels in the same stack. Both wood and metal pallets were used. A marker label was placed on each barrel for pose determination and identification using the Eagle Eye™ tracking software incorporated into the change detection system software. These barrel markers also have a greyscale pattern for real-time, automatic scaling the resulting images to normalize the pixel intensity values.

3.2.1.1.3 Computing Architecture -

The IMSS laboratory computing environment had Sun Sparcstations running SunOS version 4.1.3, connected on a laboratory ethernet. A Power PC running Mac OS v7.5 was also connected to the laboratory network. (See Figure 2)

3.2.1.2 Software

3.2.1.2.1 ABCD Image Processing -

The image processing for change detection is done on the Apple Power PC. After the images are transferred from the host workstation for the IMSS platform, they are converted to "pict" format. The pose of the barrel label is then determined using the Eagle Eye™ barrel marker tracking software. The pose of the barrel marker is used to determine the location of the illumination normalization pattern on the marker, and this information is passed via file I/O to the image processing application, currently constructed around the IPLab image analysis application for the Power PC. Images are then normalized for variance in illumination by subtracting the ambient image and adjusting the range of the pixel values of the resulting image. Specular reflections are masked to prevent them from appearing as false positive changes in the image subtraction. This is done using a technique that detects the reflected 'hot spots' in the image using a gradient technique. The prepared images are collected as either baseline or inspection images, with the final change detection process performing the image subtraction between the two sets of images, and collecting the resulting change statistics. A filter on the resulting change size and intensity places the detected changes into different categories, i.e., significant changes, moderate changes, etc.

All the image processing functions are coordinated by the Image Processing Manager (IPM), that creates the socket interface and processes the messages from the ABCD Control process.

3.2.1.2.2 ABCD Control -

The ABCD control process runs on a separate UNIX workstation, and coordinates the various image processing functions and file transfers. It communicates via a TCP socket connection to a routing process that has a socket connection to the IPM. The control process first translates the names of the collected image files from the naming convention used on the IMSS platform to that used by the ABCD image processing process. It then issues the commands to the ABCD image processing to prepare each file by converting it from raw to pict, locating the barrel marker, generating the coordinates for the illumination normalization pattern, subtracting the ambient image, and masking the specular reflections. The control process then issues the commands for subtracting the inspection image from the baseline image and renaming the results.

3.2.1.2.3 IMSS Control -

The IMSS control process was a subset of the extensive software developed to allow the IMSS to autonomously navigate the warehouse aisles, collecting barrel image data for analysis. The functions used in this testing allowed an operator to interactively position the robot on a given barrel stack, and collect a set of inspection images, both with the lights on and off. These images were then transferred to the ABCD image processing application using ftp.

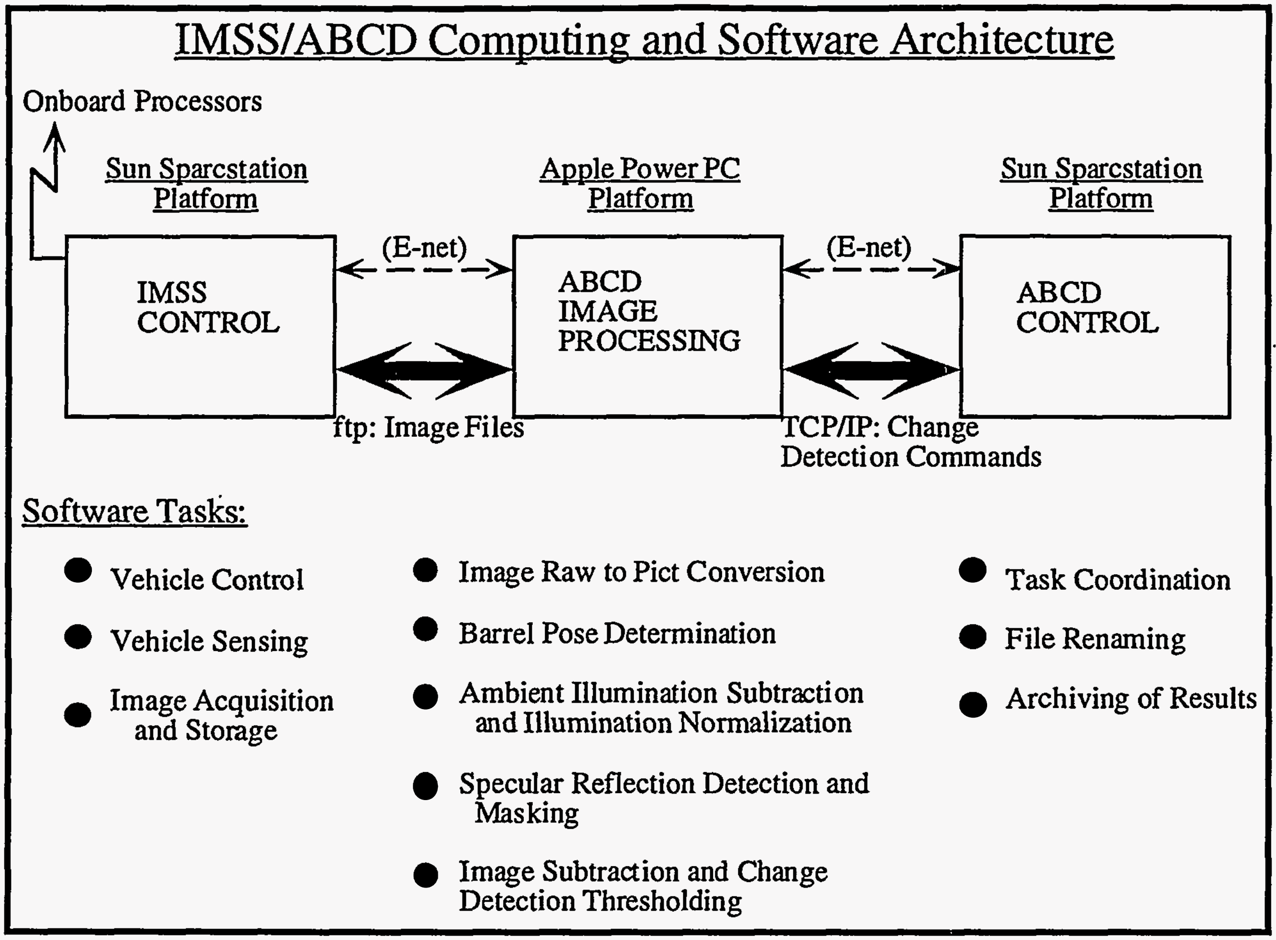


Figure 2. ABCD/IMSS software and computing architecture.

3.2.2 Test Procedure

Our test procedure was separated into two separate procedures; barrel array image collection and off-line image analysis. For this test, it was decided to not attempt to perform the change detection on each collected image in real time due to the software integration issues between the ABCD and IMSS processes.

The image collection procedure consisted of first collecting a set of barrel baseline images and then several sets of barrel inspection images. 4 images were collected for each of the 10 barrels at 2 light levels, for a total of 80 images collected for any given baseline or inspection run. The baseline condition before any test defects had been placed on the barrels is shown in Figure 3. This set of drums was chosen to represent a variety of colors and surface reflectivities. Some of the drums had glossy surfaces, some were covered with dust, some were dented. They were all placed on the pallets at varying positions relative to each other. Once a set of baseline images had been captured successfully, a collection of test defects were placed on the barrel. (see Figure 4)

Inspection runs were made by first moving the IMSS platform to center on each barrel stack in the array. Once centered, a set of images was captured first with the sensor pod pitch axes pointed up, and then down. The lights were then turned off, and a second set of images was captured, again with both up and down camera views to capture the four quadrants of each barrel in the stack. Each time that the IMSS platform was centered on a barrel, the front and rear position of the vehicle were recorded on graph paper fixed to the floor. This data was collected to gauge the IMSS positioning accuracy, to relate it to the performance of the change detection system.

The image analysis procedure consisted of transferring the image data files from the IMSS host computer for both the baseline and inspection image sets, going through an image preparation process, and then performing the change detection between baseline and inspection runs. The image transfer was done manually, through a simple file transfer. The image preparation process, resulting in images ready for change detection, required approximately 2 hours to run for a given barrel array data set. The change detection required 1 hour to run on a barrel array data set. The limitations of the time requirements for the image analysis will be discussed in section 4.

3.2.2.1 Defects

The test defects placed on the barrel (see Figure 4) were designed to have a variety of shapes, colors, contrasts, and locations on the barrels. They were chosen to test the performance of the ABCD change detection system with respect to the features that would be seen in actual defective barrels in the warehouse, such as rust, corrosion, leaks, and blistering. In Task 2, a performance specification was determined and verified for the ABCD system, that required detection of 1/4" or larger defects, with contrast differences of at least 20% from their background, at angles of less than 40 deg. off the barrel centerline. This was under the conditions of having camera re-registration to within 1mm and the necessary on-board light power.

For the IMSS/ABCD tests, a set of test patterns was produced to see if the system now integrated with a mobile base would still meet the performance specifications. These test patterns consisted of evenly spaced white and black dots that run from the barrel centerline to 60 deg. off the centerline. These test patterns were placed on barrels of a range of colors from black to white. The data from these patterns provided the detection rate vs. angle from barrel centerline and false positive data.

In addition to the test patterns, red splotches were placed at various places on some barrels to represent rust spots. These were relatively low contrast changes when viewed on a black barrel background. White powder was thrown on some barrels, and streaks were made in the existing dust on others. An extra radiation hazard label was placed on one barrel to examine false positive detections due to relabeling of barrels. And lastly, for one inspection run, water and oil was sprayed on the magenta colored barrel and allowed to drip down the front surface.

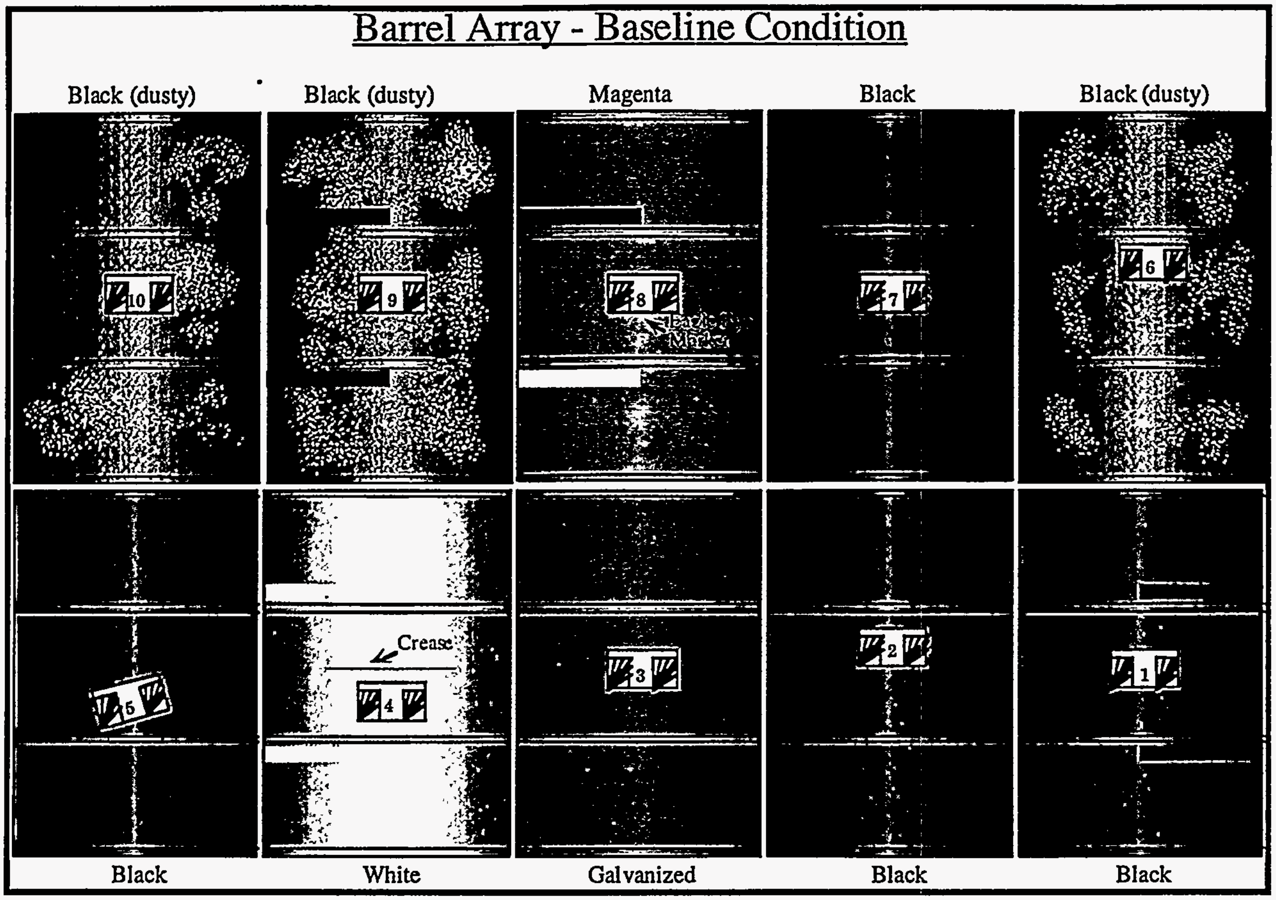


Figure 3. The barrel array, shown here in the Baseline Condition, included a variety of barrel colors, label placements, and existing but benign features.

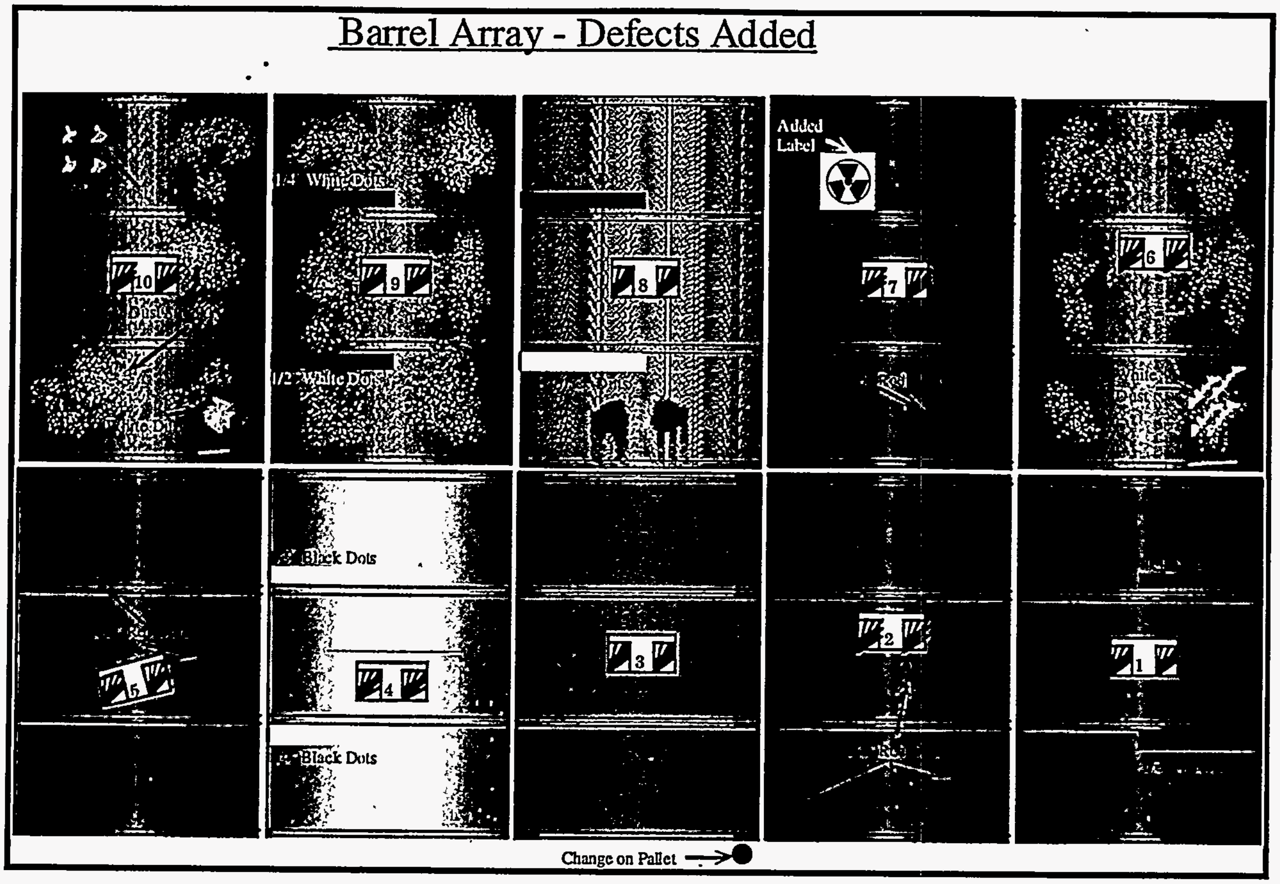


Figure 4. The barrel array, shown here with "defects" added to the baseline condition, included those most critical to warehouse operators: rust, streaks, leaks, new labeling, unspecified changes in appearance, and pallet changes.

3.2.2.2 Run Matrix

Three baseline data collection runs and six inspection data collection runs were performed on two separate arrays. The first array was the 10 barrel array described in the previous section. In addition, a mockup of a B25 waste storage box was setup in the laboratory, with Eagle Eye™ markers attached, and baseline and inspection runs were executed on the mockup. Unfortunately, due to a problem with the camera iris setting, most of the images collected were not able to be tracked with the Eagle Eye™ software, so meaningful change detection information was not produced.

A summary of the runs for which data was collected is presented in Table 1. For each barrel visit, 8 images are collected; two cameras, each imaging the top and the bottom quadrants of a barrel and imaging with only ambient light and with ambient plus IMSS light (2 cameras, 2 views per camera, 2 lighting conditions). A run visited 10 barrels or 10 points on the B25 box mockup. Thus 80 images were collected in each run. For each of these runs, the 80 image files were stored, along with the IMSS starting and stopping positions. In addition, after the image processing, the normalized, ambient subtracted images were stored. The difference images, registration shift record files, files recording illumination normalization pattern position, barrel label pose, and the results of the significant and moderate change detection were also stored for each barrel view.

Run #	Run Type	Array Type	Defect Type	Comments
1	Baseline	10 Barrel Array	N/A	Camera 1 Misadjusted
2	Inspection	10 Barrel Array	All	Camera 1 Misadjusted
3	Inspection	10 Barrel Array	All	Camera 1 Misadjusted
4	Inspection	10 Barrel Array	All	Camera 1 Misadjusted
5	Inspection	10 Barrel Array	All	Camera 1 Misadjusted
6	Baseline	10 Barrel Array	All	Adjusted Cam 1 Iris
7	Inspection	10 Barrel Array	All + Water and Oil	Adjusted Cam 1 Iris
8	Baseline	B25 Box	N/A	
9	Inspection	B25 Box	All	Light Levels Saturated

Table 1 - Test Run Matrix. "All", where applicable, includes varying contrast, size, and color defects, as well as simulated rust, corrosion, blistering, dust, streaks, and added labels.

3.2.3 Results

The results for the change detection tests are presented in this section, to show 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.

3.2.3.1 Case by Case Defect detection

Figure 5.1 shows a representative change detection result for the test pattern with 1/2" black defects on a white background. For this case, the detection rate was 100% and no false positive detections were found. Since the 1/2" defect size is larger than the required minimum defect size, and the contrast difference with the background is 100%, the successful change detection results are not surprising. In addition, the IMSS repositioning error was low for this inspection run. However, the glossy white surface on barrel number 4 did give problems in the specular reflection masking process for other runs.

Figure 5.2 is the change detection results for a representative case with the test pattern containing 1/4" white defects on a black background. In this case, since the changes are smaller, the detection rate is only 67%, while there are still no false positive detections. It should be noted that in this case, as in the case in Figure 5.1, the specular reflections, barrel label, and background are entirely eliminated in the difference image. This is the advantage of an image subtraction approach for defect detection over an image analysis approach, which might be confused by other features in an image that closely resemble the type of defect of interest.

Rust splotches were simulated in inspection run 2, on the upper left quadrant of barrel 2. An example change detection result is shown in Figure 6. The red defects are detected out to past the specified 40 deg. from barrel centerline, even with the reduced contrast difference for the red color on a black background. Again, the barrel label and background are entirely removed in the difference image, and no false positives result from the change detection.

In an actual warehouse, barrels might be relabeled periodically, or other changes to the barrel's appearance may occur. These changes could be due to adding or removing straps, or repainting. While these changes in appearance don't signify a defect in the barrel, it is important to see what their effect would be on a change detection based inspection system like ABCD. Figure 7 shows the results from a representative inspection run where an extraneous radiation hazard label was added to the upper left quadrant of barrel 7. The change detection system successfully detects this as a single, large area of change, with no false positive detections.

An important change to detect in the inspection process is any fluid leak or dripping. While this was not the main focus of the ABCD/IMSS integrated testing, an inspection run was performed with water and oil applied to the surface of barrel 8. Figure 8 shows the results of this test run. The illumination was inadequate to produce any contrast change for these colorless liquids on the light colored magenta barrel surface. Because of this, no change was detected. This test shows the importance of the capability to vary the illumination on the barrel surface dynamically to find different types of defects.

In a laboratory setting it is easy to forget that the waste barrels that are being inspected can be located in a wide variety of environments, ranging from a controlled indoor environment to an outdoor environment subject to changes in the weather. In order to give some of the barrels a more dirty appearance, they were dusted over with a white power. If more dirt is accumulated on the surface or if streaks are made in the dirt that is there, this change in appearance will register with a change detection system. Figure 9 shows a change detection result for a representative case of accumulated dirt and Figure 10 shows a detection result where streaks in the accumulated dirt are encountered. It is interesting to note, and it wasn't anticipated during testing, that the change detection finds not only the dust that was applied to the surface of the barrel, but also the powder that fell off the barrel and accumulated on the barrel chine at its base. This can be seen in the lower right quadrant view in Figure 9. The streaks in the dirt have very little contrast difference, especially on a black barrel, but these are still detected by the ABCD system in the lower right quadrant of the image in Figure 10. Again, no false positive change detections occurred for this inspection run.

Lastly, a change detected on the pallet itself can be important for finding fluid accumulation due to a corrosive rupture of the barrel. To test for this, on the pallet under barrel 3 a red spot was placed. Figure 11 shows a typical result of the change detection for this case. The pallet change is detected. However, there are false positive change detections for this case along the barrel chine. This barrel had a galvanized surface and was particularly reflective, so these false positives result from the difficulty in detecting and masking specular reflections.

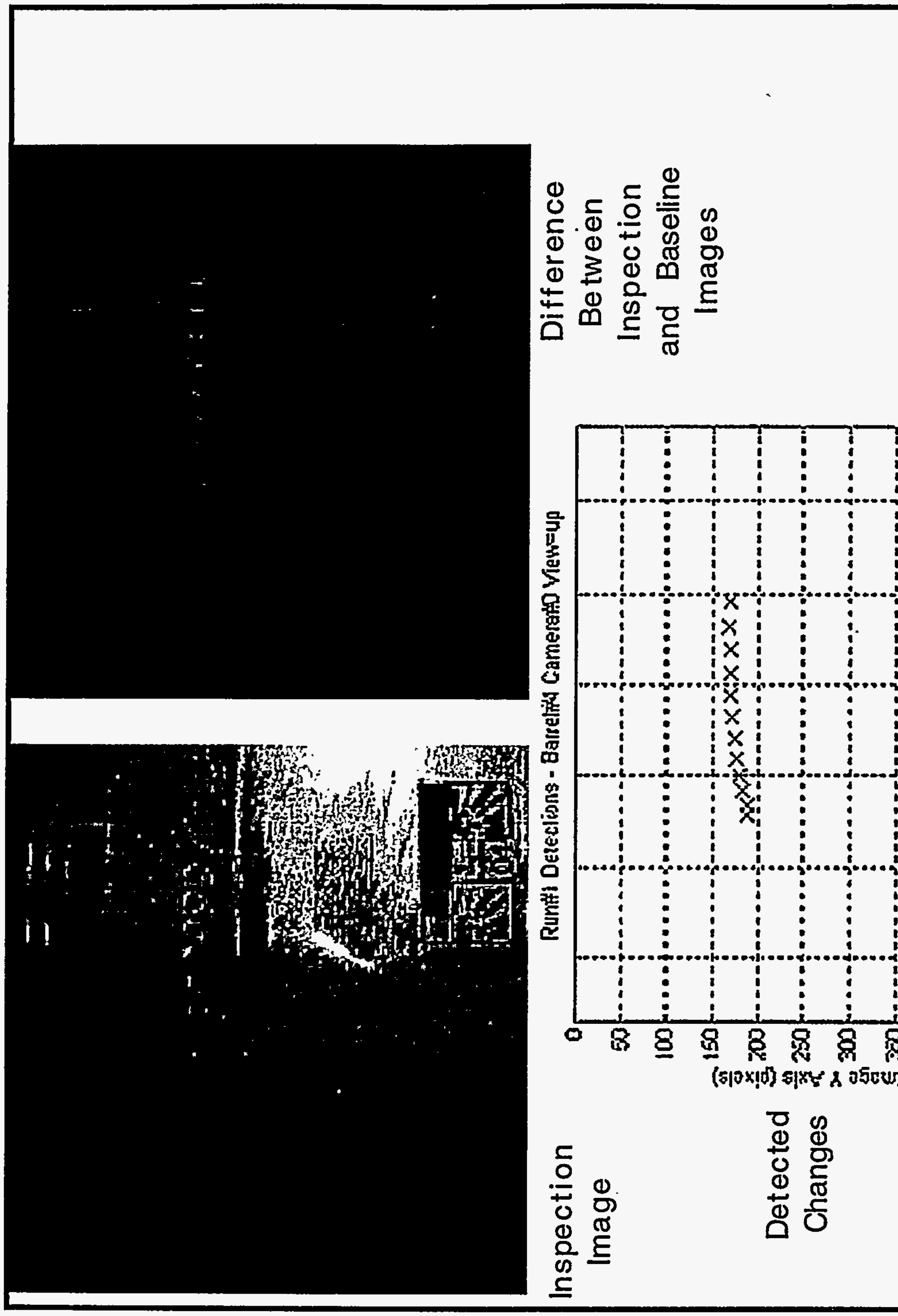
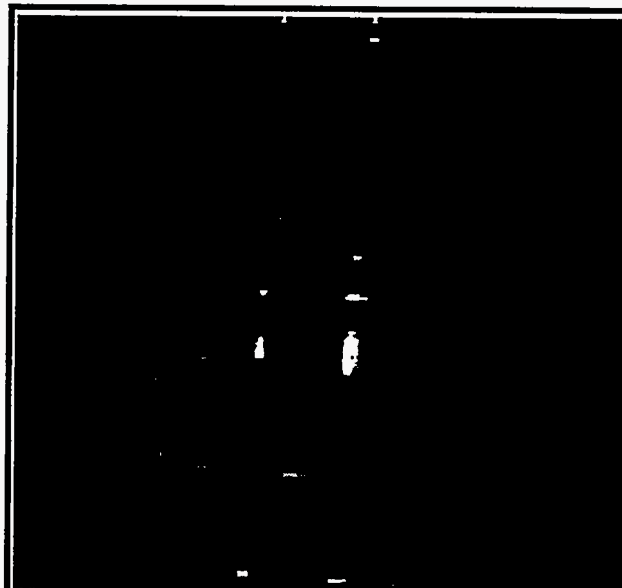
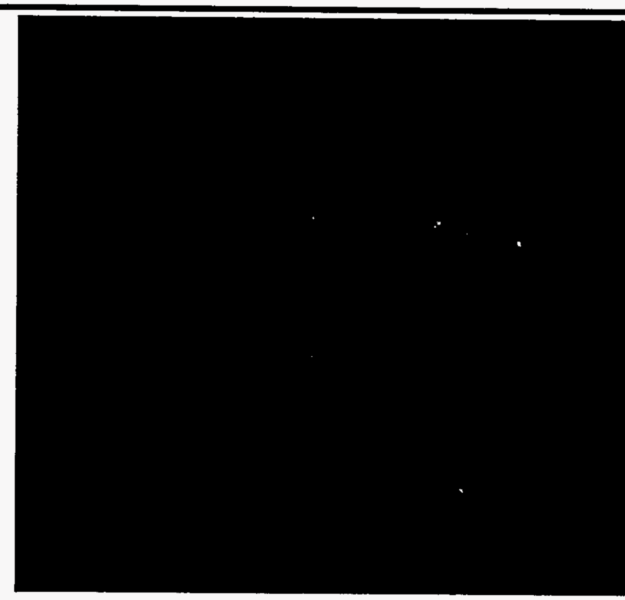


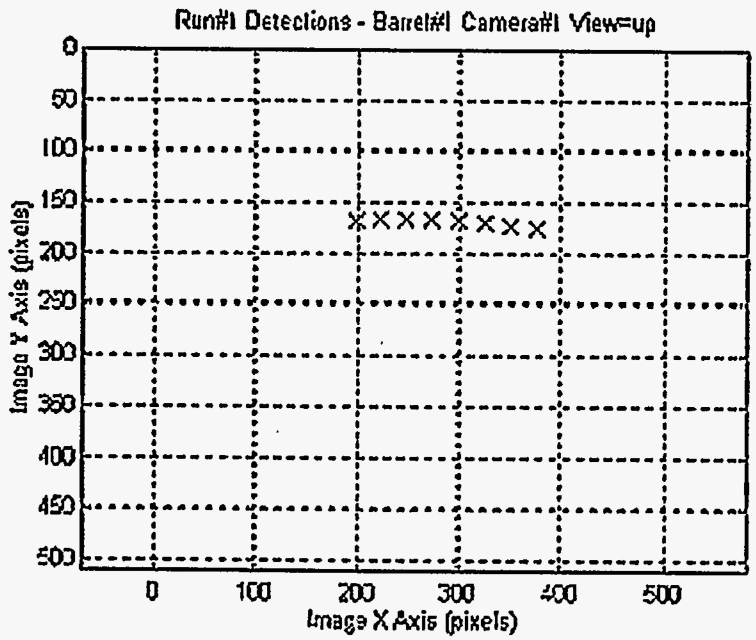
Figure 5.1. Run 1, Barrel 4, Camera 0, View Up - 1/2" Black Dot Defects



Inspection Image



Difference Between Inspection and Baseline Images



Detected Changes

Figure 5.2 Run 1, Barrel 1, Camera 1, View Up, with 1/4" White Dot Defects

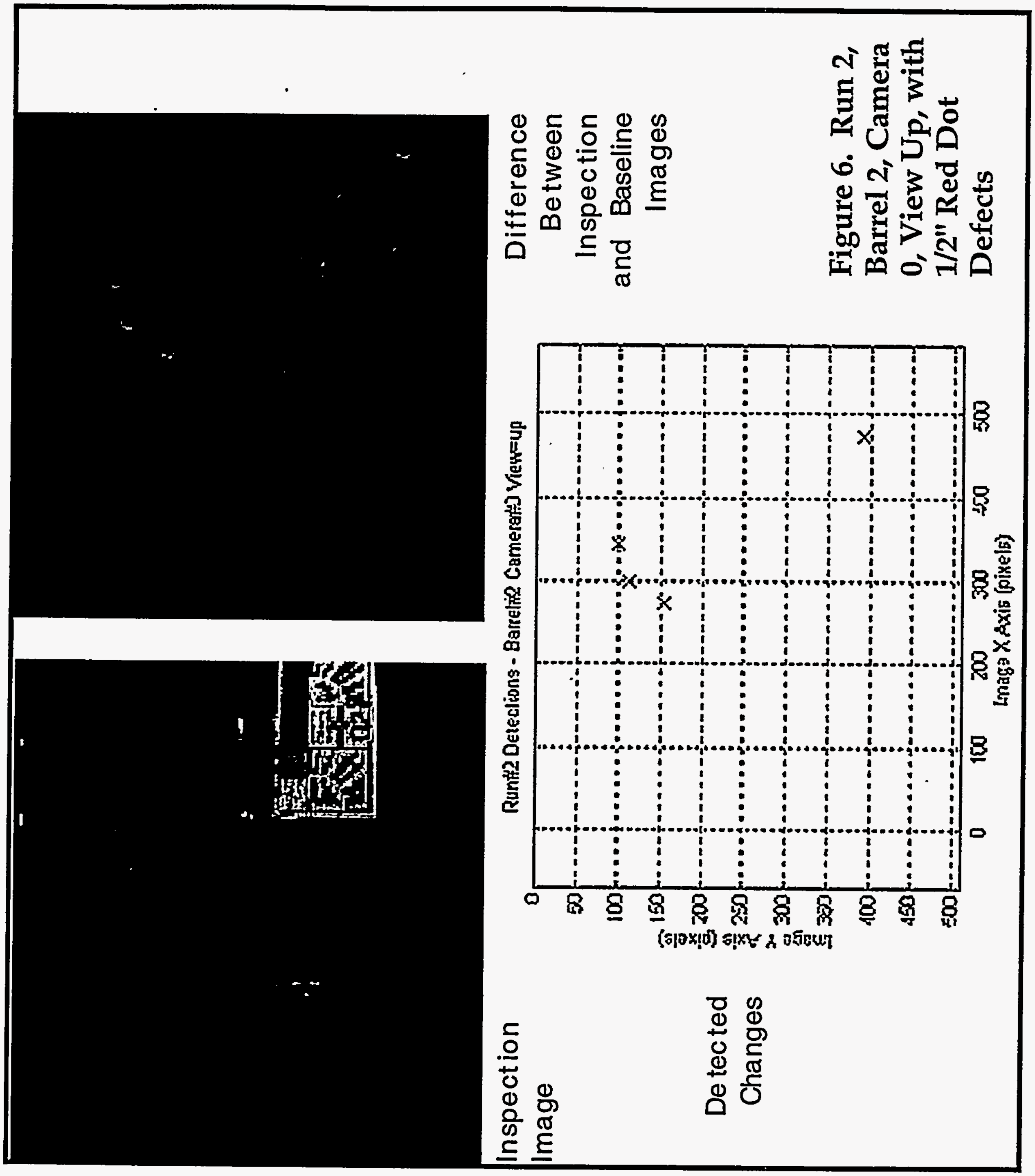


Figure 6. Run 2, Barrel 2, Camera 0, View Up, with 1/2" Red Dot Defects

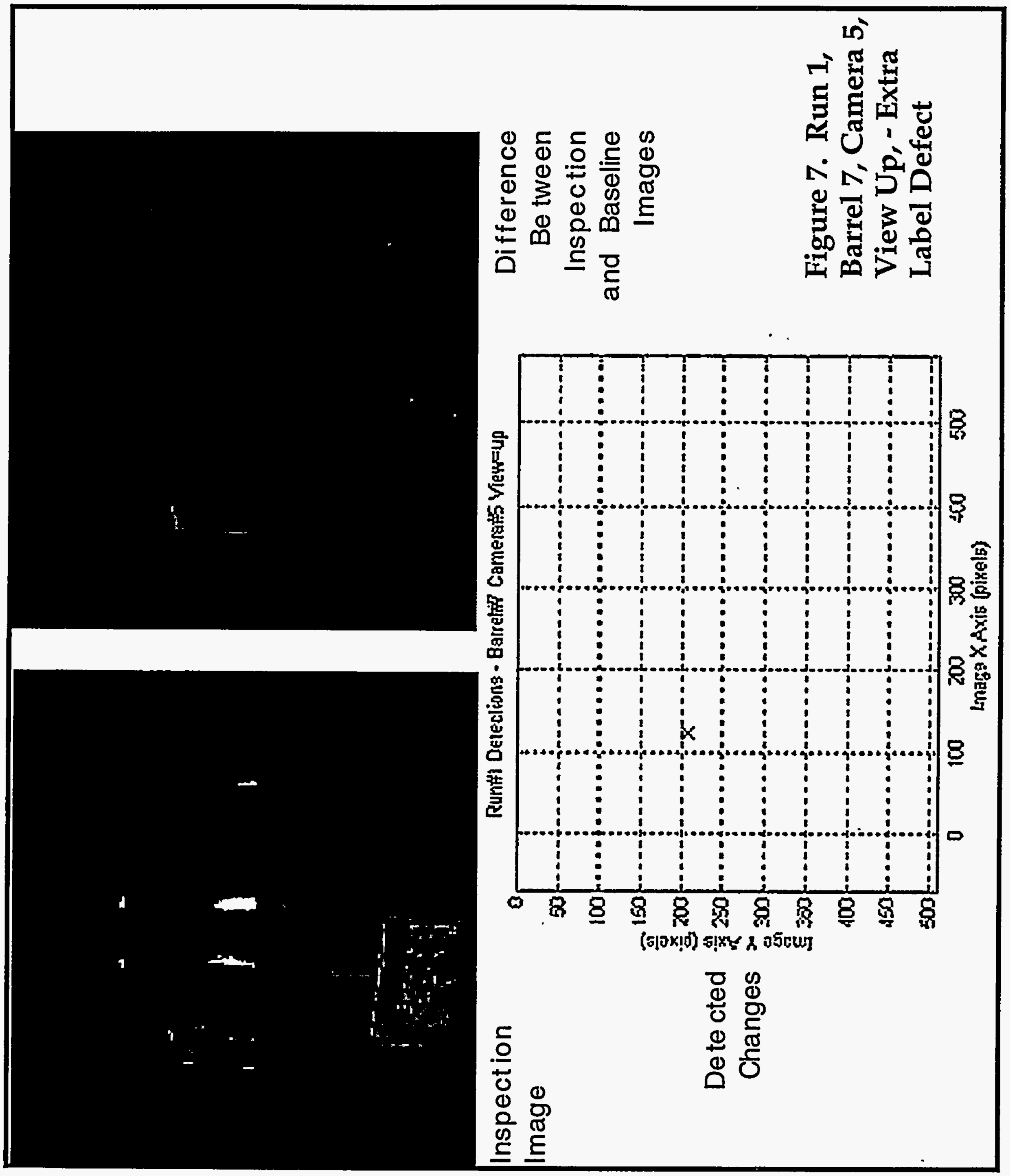


Figure 7. Run 1, Barrel 7, Camera 5, View Up, - Extra Label Defect

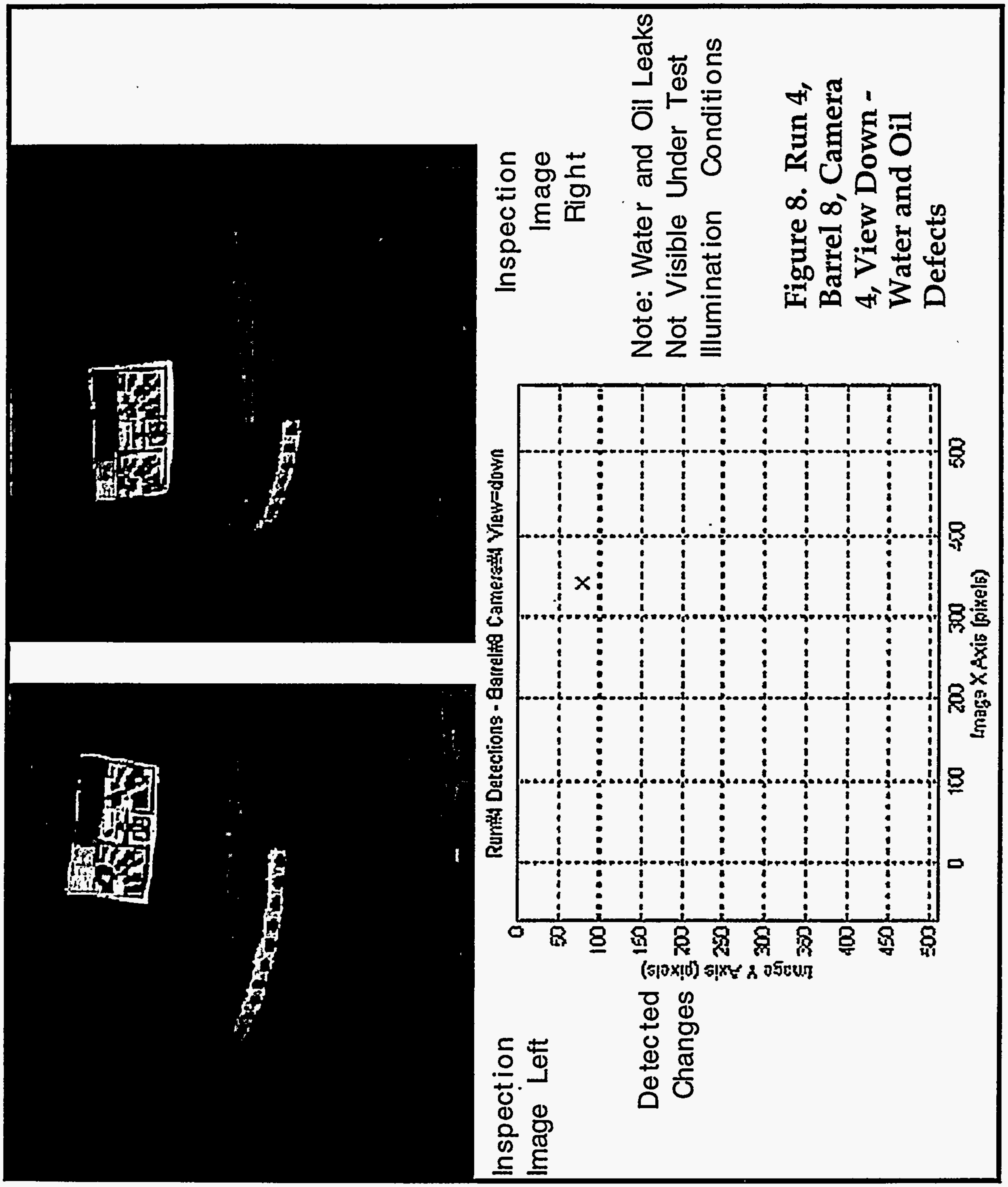


Figure 8. Run 4, Barrel 8, Camera 4, View Down - Water and Oil Defects

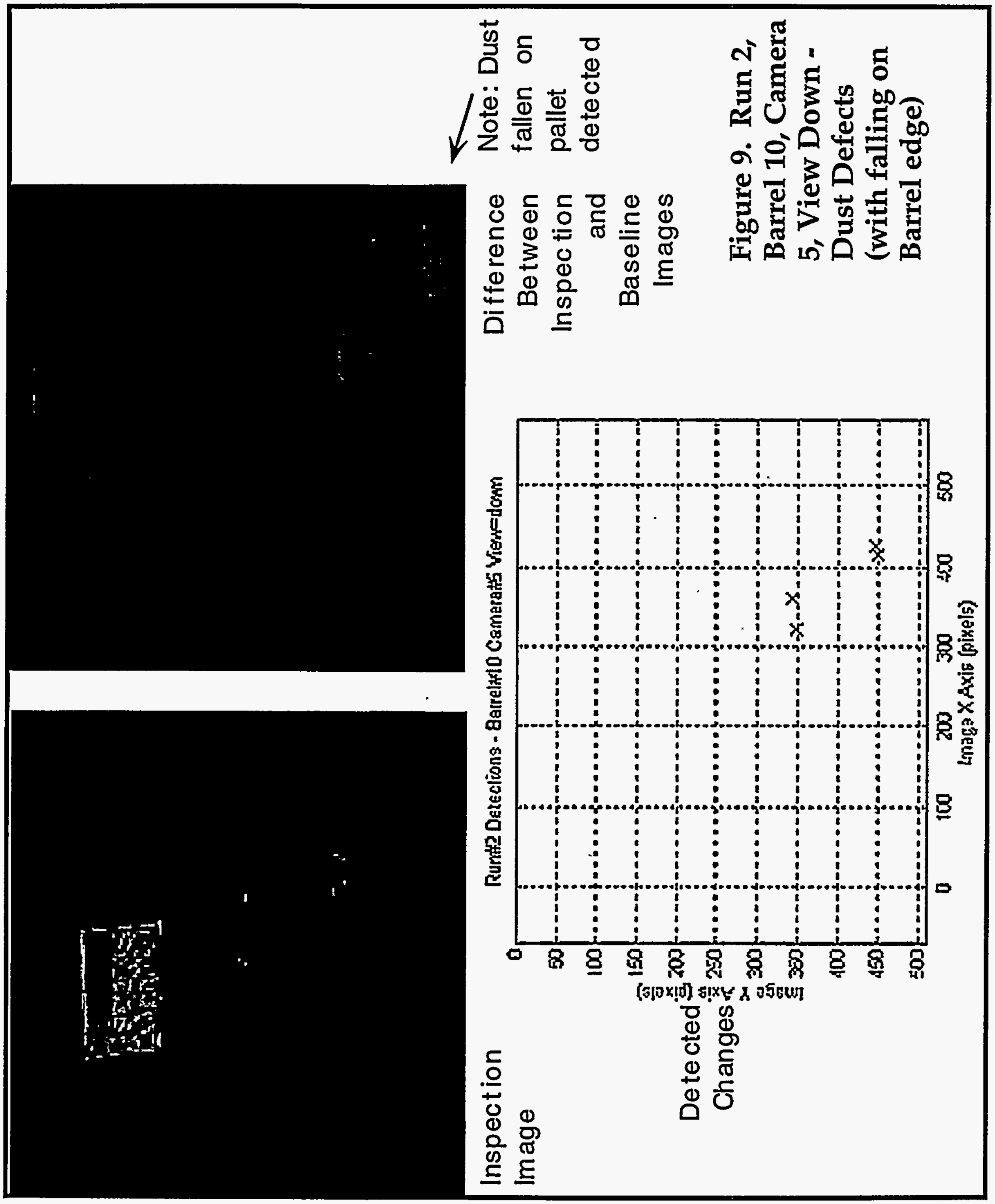


Figure 9. Run 2, Barrel 10, Camera 5, View Down - Dust Defects (with falling on Barrel edge)

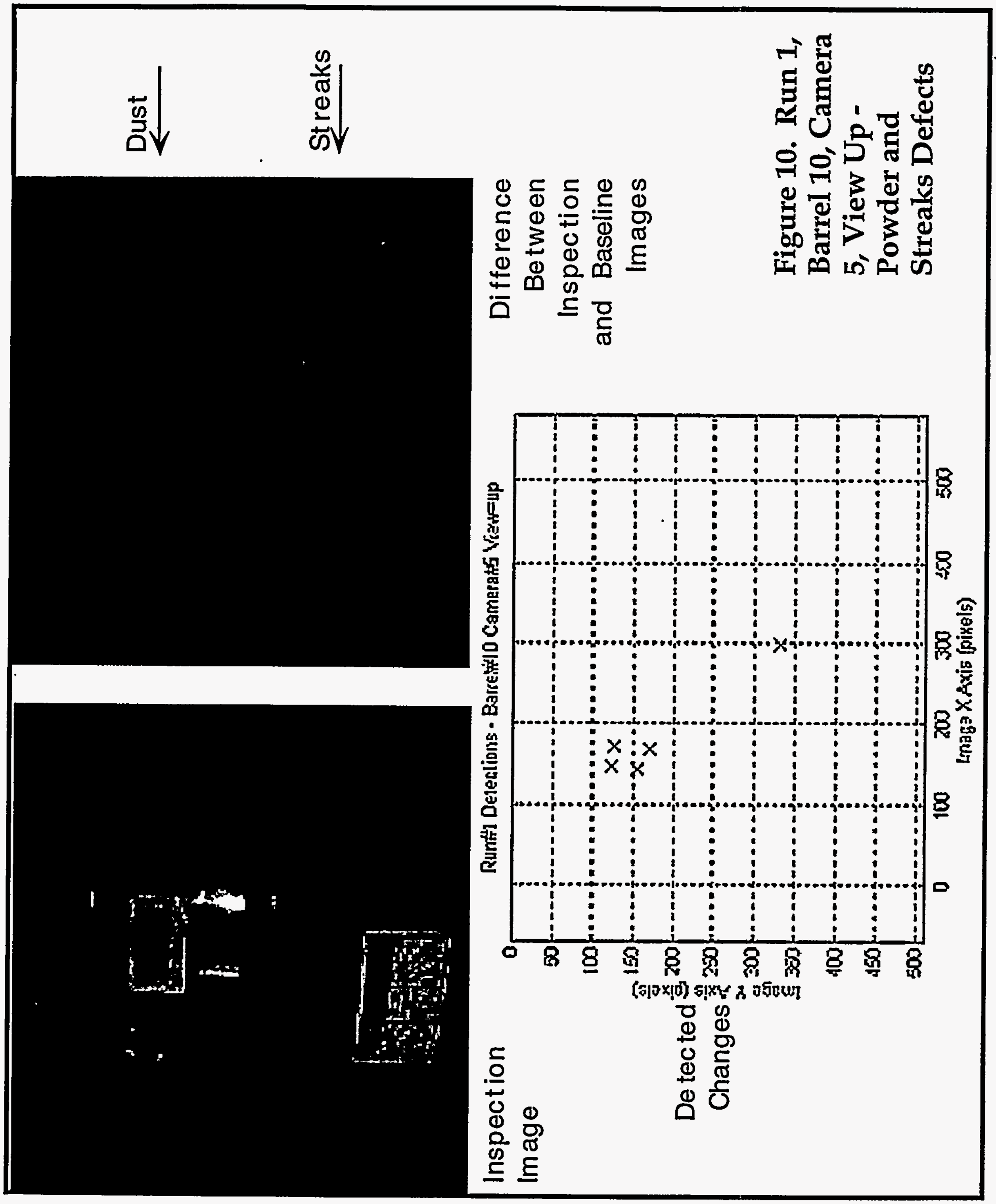


Figure 10. Run 1, Barrel 10, Camera 5, View Up - Powder and Streaks Defects

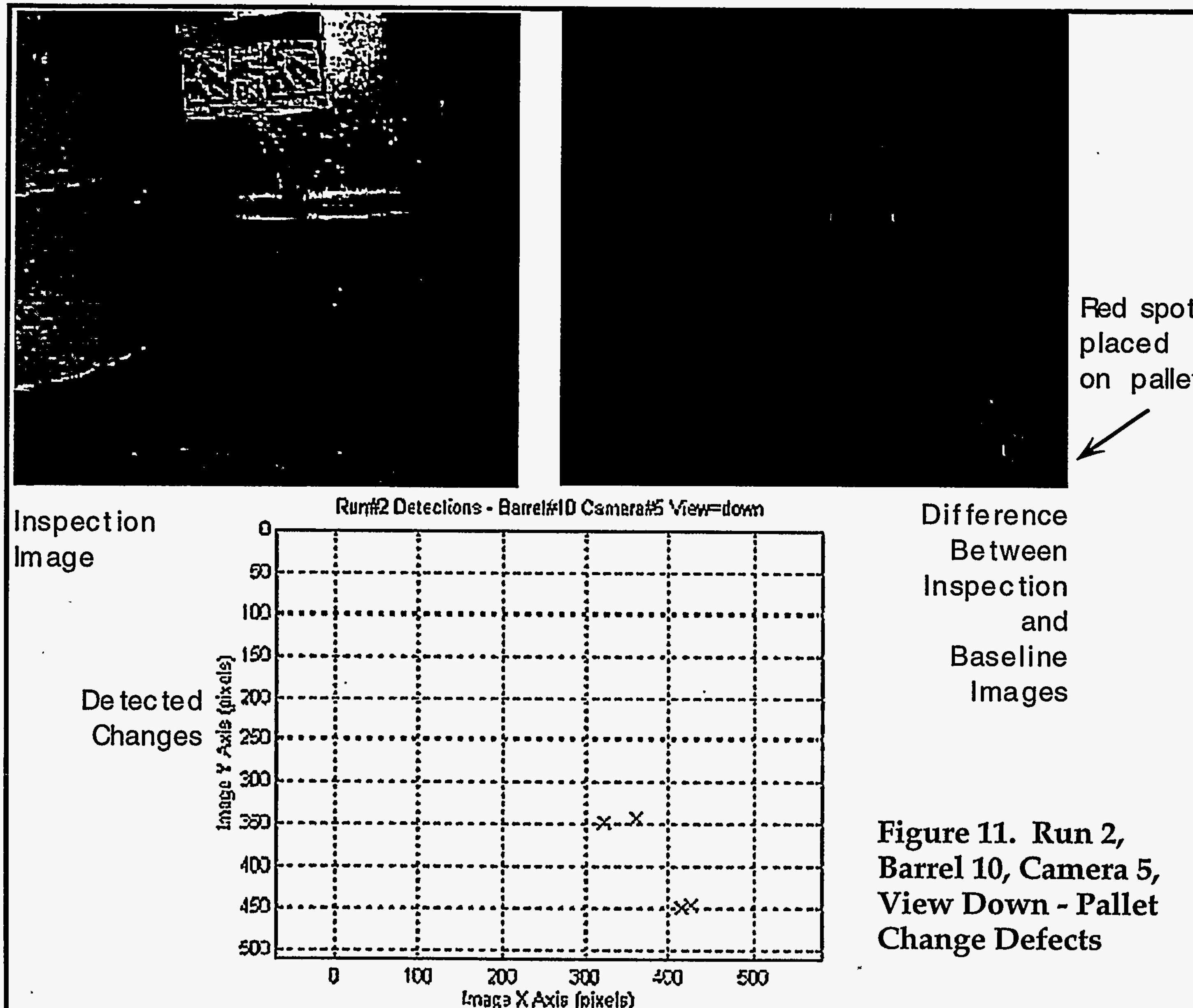


Figure 11. Run 2, Barrel 10, Camera 5, View Down - Pallet Change Defects

3.2.3.2 Detection rate curves

The data from the change detection inspection runs for the barrel views that included the radial test patterns was reduced to produce a set of average detection rate curves versus angle off of barrel centerline for each of the test patterns. These curves are plotted in Figure 12 for the 1/2" size defects, and in Figure 14 for the 1/4" defects. An average of these detection rate curves over all the test patterns and for all inspection runs can be calculated, and is presented for the 1/2" size defects in Figure 13, and for the 1/4" defects in Figure 15. These figures show two things. First, they show the performance of the change detection out to the desired specification of 40 deg. off barrel centerline is close to that verified in Task 2. They also show that detection rate, as is to be expected, decreases faster with angle off of barrel centerline for the smaller defects.

3.2.3.3 False Positives

The number of false positive change detections was accumulated for all of the inspection runs. Data was included from all runs for which there was a successful pose determination of the Eagle Eye™ label, the inspection image was successfully registered with the baseline image, and the camera iris was correctly adjusted. Problems with noise in the video, and lack of illumination in some cases, caused poor tracking and registration of images. When these effects are accounted for, a histogram of false positive detections can be plotted for all the inspection runs. This plot is shown in Figure 16. The plot shows that there is a rapid drop off of inspections having an average number of false positives greater than 1. The outlying cases in this histogram are usually for barrels with more reflective, light colored surfaces where specular reflections are difficult to either subtract out or detect and mask out.

2.3.4 Summary

The data for detection rate and average false positive occurrence per inspection run is summarized in Table 2. The data has been calculated for each of the different types of defects that were used in the tests along with some clarifications. Again, detection rate is lower for smaller defects, or for defects with lower contrast, such as the red colored changes. False positives are more predominant on light colored barrels and barrels with reflective surfaces. For the cases where dirt and streaks were put on the barrels, it is ambiguous what number of changes one should say are true positive and what are false positive, so the false positive detection rate for these cases is less clear.

Defect Type	Avg. Detection Rate	Avg. False Pos. per Insp.	Comments
1/2" White Defect	93.8%	2.32	Light colored (magenta)
!/2" Black Defect	93.0%	.6	
1/4" White Defect	65.8%	1.533	Lower due to smaller size
1/4" Black Defect	85.4%	.4	
1/2" Red Defect	64.3%	.875	Low contrast
Extraneous Label	90.0%	.4	
Dust	98.8%	2.35	False positives ambiguous
Streaks	74.3%	8.33	Low contrast
Water and Oil	----	.1	Not enough illumination
Pallet Changes	100%	.8	Limited Runs

Table 2 - Summary of Average Detection Rates and False Positives per Inspection

3.2.3.5 IMSS Repositioning Capability

One of the basic premises of the ABCD inspection technique is that images from a baseline inspection run and a subsequent inspection run at a later time can be successfully registered with each other for image subtraction. This image registration is accomplished partly in the hardware, by placing the camera in as close to the original position where the baseline image was taken as possible, and partly in software, where an image tiling technique is used to match features in one image with those in another to produce a peak correlation. An important result of the testing of the ABCD/IMSS integration is the impact of the repositioning capability of the IMSS mobile platform on the change detection results. During Task 2, we found that successful image registration could be accomplished even for camera repositioning errors on the order of 1-2 cm. Figure 17 shows a histogram of the magnitude of the horizontal camera repositioning error for all the inspection runs. The mean error was .75 cm, and the standard deviation of the error was .76 cm. These fall within the range that was verified in Task 2, and the change detection results confirm this.

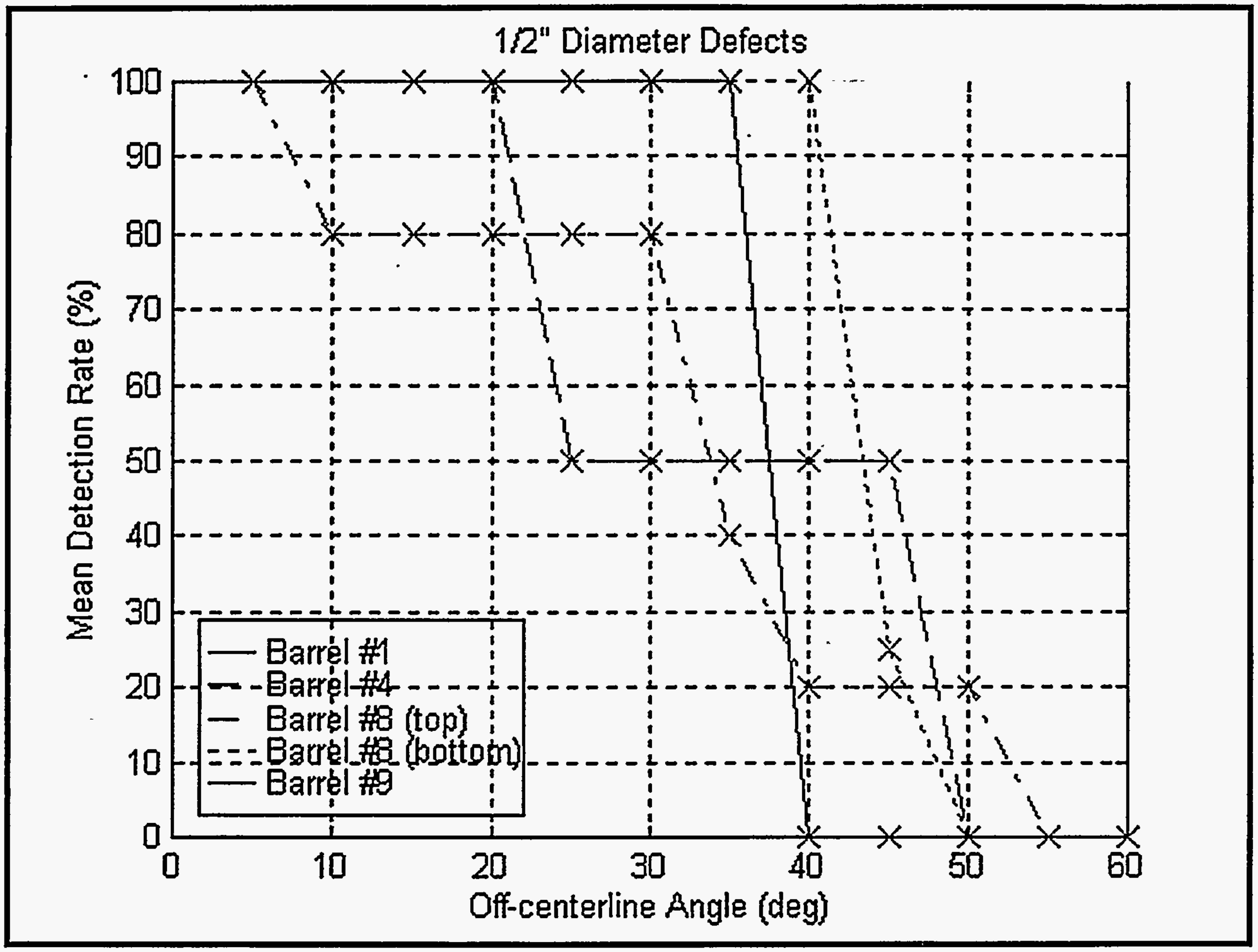


Figure 12. Shown for five different views of four different barrels are the mean change-detection rates as a function of the off-center angle of the change. These data are for 1/2″ dots in all runs.

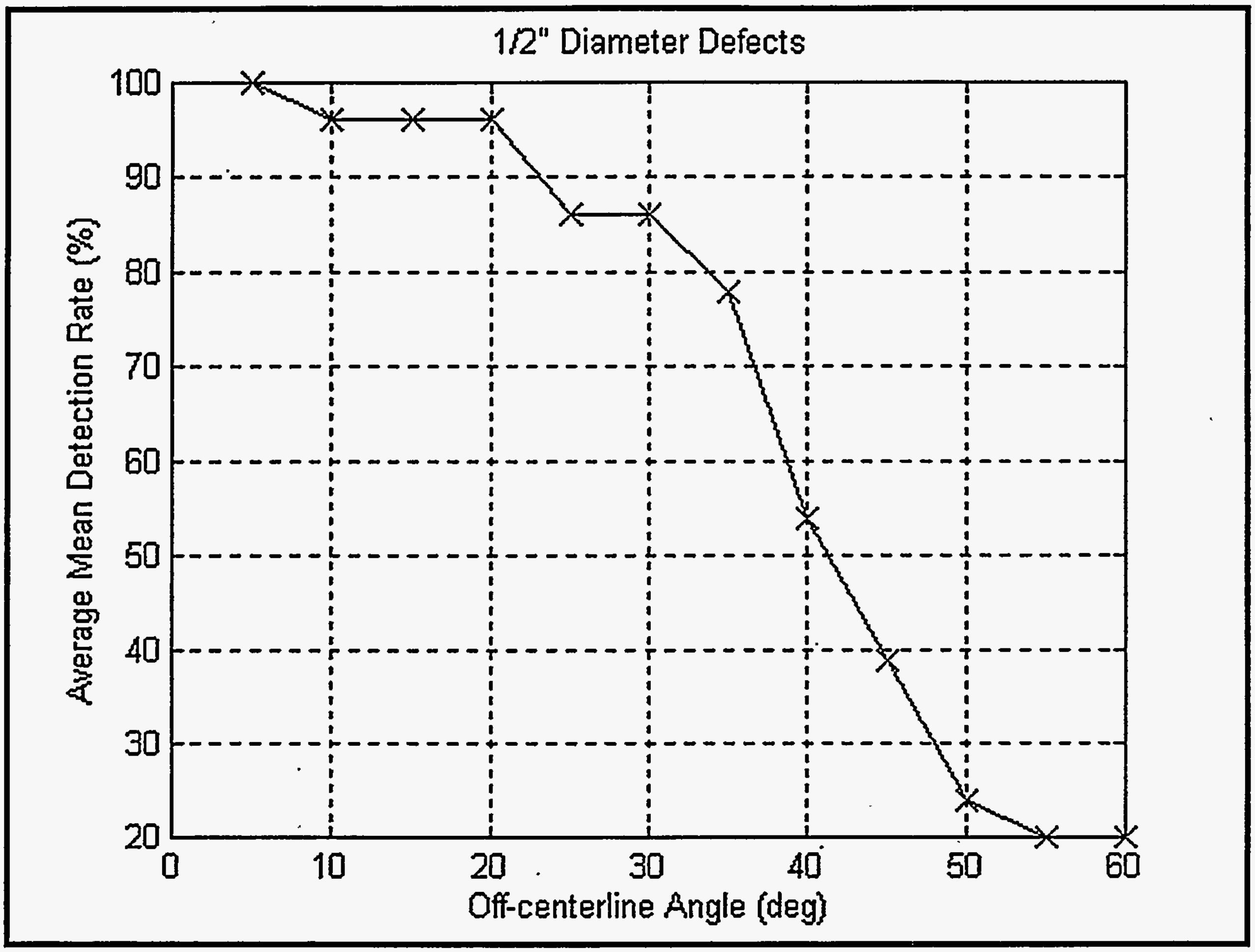


Figure 13.. Shown as the mean of five different views of four different barrels is the mean change-detection rate as a function of the off-center angle of the change. These data are for 1/2" dots in all runs.

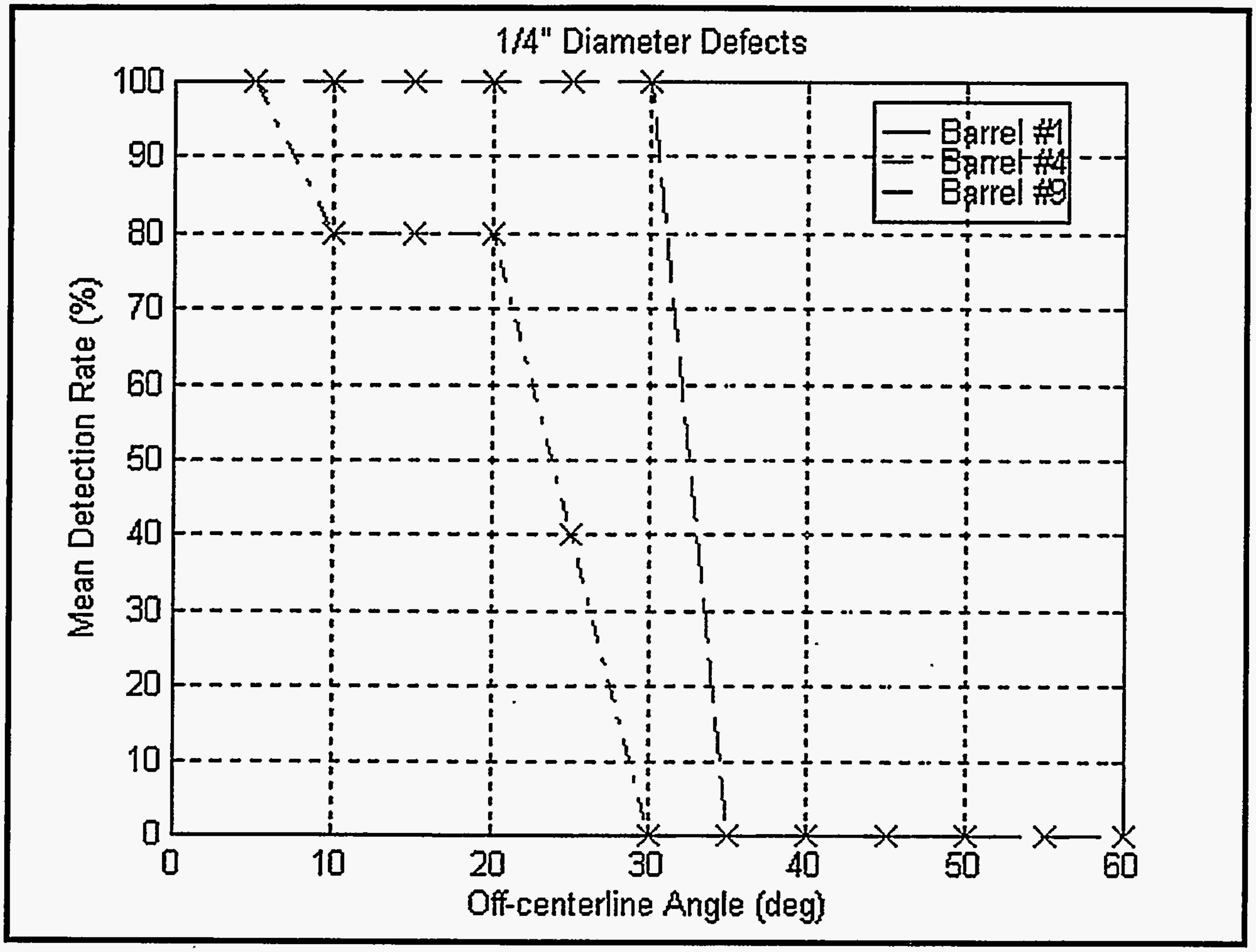


Figure 14. Shown for three different barrels are the mean change-detection rates as a function of the off-center angle of the change. These data are for 1/4″ dots in all runs.

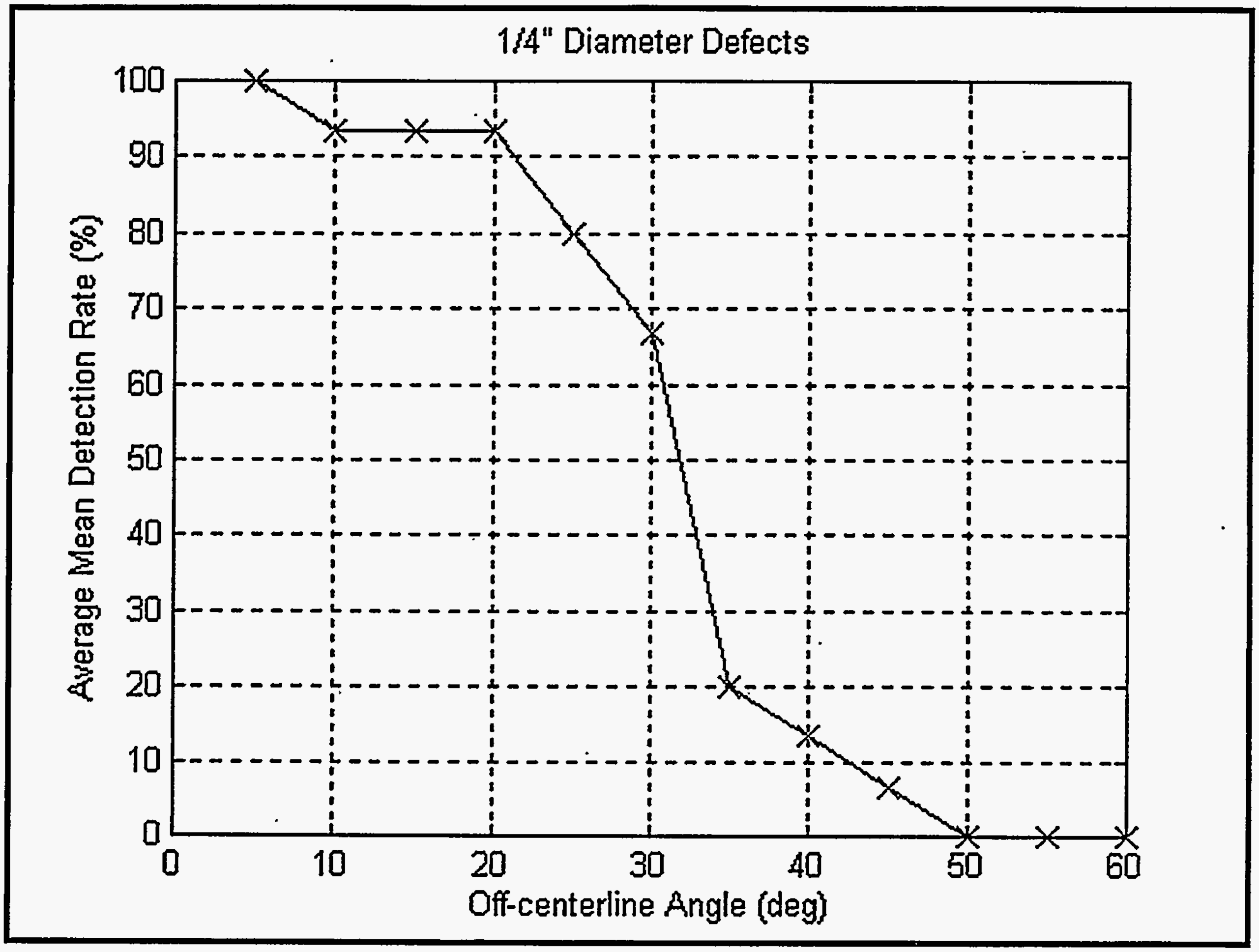


Figure 15.. Shown as the mean of three different barrels is the mean change-detection rate as a function of the off-center angle of the change. These data are for 1/4″ dots in all runs.

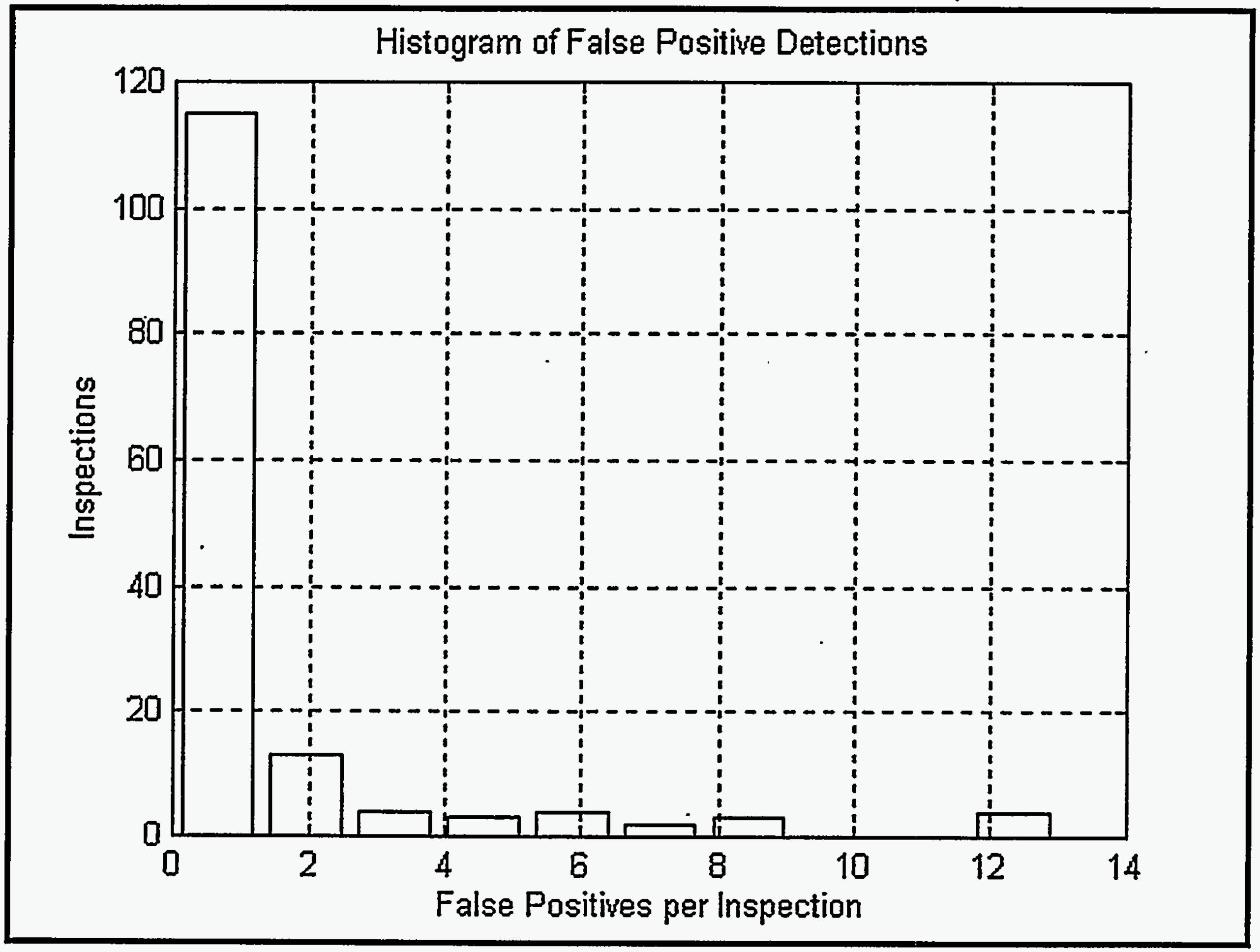


Figure 16. Shown is the frequency distribution of inspections with false-positive change-detections.

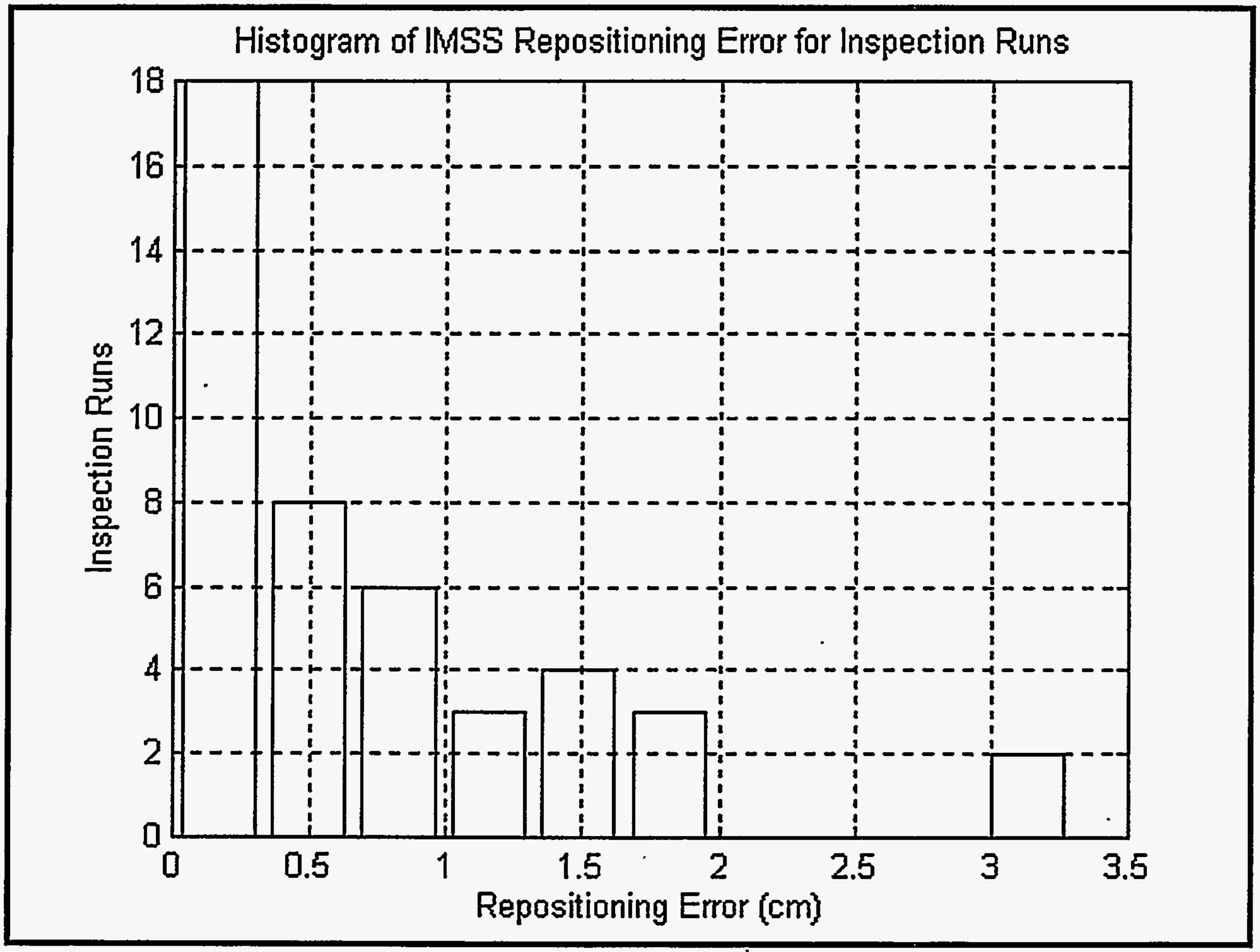


Figure 17. Shown is the frequency distribution for IMSS repositioning.

3.2.4 Discussion of Results

The purpose of performing these tests with the ABCD change detection system installed on the IMSS platform was to bring to light the problems that will be encountered when trying to create a field ready barrel inspection system. Many problems were encountered during this testing, and many areas for future work in creating a more useful inspection tool were identified.

3.2.4.1 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 ABCD system software was designed with an extremely flexible interface in that any process that can create TCP socket connections can interface to the change detection system. However, the applications themselves were built around a commercial image processing application (IPLab) that runs only on the Power PC and is not portable to other platforms. While giving flexibility and generality during development, this application limited the performance of the final ABCD system in terms of portability and time required for a detection..

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. This should not be challenging once the interface between the two systems is designed, as both are available as C source code and both have been shown to compile and run on identical platforms.

The second step in creating a more robust system software would be to port the ABCD image processing functions to source code. This could be accomplished in two ways. The functionality of the image processing steps carried out by IPLab could be directly translated into a source language. This would be an intensive software development task and is not recommended. The second method would be to find another PC based image processing tool similar to IPLab, but one that has the option that once an image processing application is developed, the tool will generate the source code to implement the application. This will save time and improve the portability of the resulting code.

3.2.4.2 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, but would only be useful if there is feedback from the image process routines to let the data acquisition process know that the current light level is inadequate. This will be remedied by future efforts to improve the integration and performance (speed) of the system software, to produce a truly integrated, real-time inspection system.

3.2.4.4 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. In several inspection images, particularly ones where the label was deliberately placed a distance away from the center of barrel (see barrels 2, 4, 5, and 6), the label was cut off in one or more of the quadrant views of the barrel, causing a failure in the change detection. If real-time feedback were available from the image processing routines to let the IMSS control know that the Eagle Eye™ marker had failed to be tracked, the IMSS platform could be repositioned for another image acquisition.

3.2.4.3 Video noise

The performance of the change detection was limited in many cases during this testing by a high level of noise in the video signals. This noise has been attributed to either the DC/DC converter used for the camera power, or to EMI encountered by the video cable during routing through the robot body. The noise made many images particularly hard to register, especially in low light conditions. Since the software registration technique using correlations of subtiles of the image looks for correlation peaks between smaller subsections of the baseline and inspection images, noise in the video signal could introduce 'false texture' that the image tiles would find correlation peaks in, resulting in misregistration.

3.2.4.5 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. Currently, performing change detection on one quadrant view of one barrel requires approximately 3.5 minutes. 1.5 minutes of that total is taken up by a bug in the Mac OS file I/O that causes file opening to take an inordinate amount of time when a folder contains a large number of files. The remaining 2 minutes are mainly taken up in converting the image file format, specular mask generation, and image registration. The speed of these functions could be significantly increased by translating them to source code that could be optimized and compiled. 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. Currently only a single processor is used to detect changes on each inspection view serially. But it is conceivable that separate processors could be used to analyze the image data in parallel.

3.3 ABCD Phase 1 Task 3 Conclusions

The ABCD system more than met its Phase 1 Task 3 objectives. The primary objective of inspecting an array of barrels was achieved with more barrels and a wider variety of barrels than originally planned. To help achieve this, we upgraded and enhanced the ABCD software to be much more robust with respect to camera repositioning with a new tiling registration scheme. We developed a more robust label that gave higher reliability for pose determination, good texture for tiling registration, and improved light-intensity normalization. And the image processing capabilities, especially with respect to automatic masking of specular reflections, was made more reliable.

While additional refinements are still required, especially for integration of ABCD with other DOE systems, the results presented here establish the ABCD system as a practical and well-understood approach for helping to satisfy DOE inspection requirements.

PHASE 1 TOPICAL REPORT

ATTACHMENT 4

Automated Baseline Change Detection

Task 4 Summary Results

Attachment 4 Contents	Attachment 4 Page Number

PHASE 1 TOPICAL REPORT

ATTACHMENT 4

Automated Baseline Change Detection

Task 4 Summary Results

Change-Detection ER&WM Field System Compatibility Verification

A4.0 General

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

This objective was accomplished through the collaboration of the DOE METC CORs and the contractors for the four DOE major robot-based barrel inspection programs. In Phase 1 the ABCD project is primarily concerned with the images of barrels and only secondarily with the mechanisms used to get the image, except that high reproducibility is required. Thus compatibility largely is verified if ER&WM requirements are mainly based on visual changes in barrels, assuming that platform mobility and agility can meet navigation and camera positioning requirements.

The ER&WM requirements are classified into Operator Requirements, Warehouse Requirements, and Mobile Platform Requirements. These are reviewed in the next three secions. The last section summaries the conclusions.

A4.1 Operator Requirements

A4.1.1 General

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

Other attendees included representatives from the DOE laboratories in Fernald, Los Alamos, and INEL. The DOE CORs for both the ABCD and IMSS projects led the DOE laboratory warehouse operators and the DOE-contractors in defining a collective set of DOE site requirements. Rather than be collected independently by each barrel-inspection project, including ABCD, there will be a subset of all DOE requirements that all barrel inspection projects can use as a common objective.

The current indexed list of inspection features is given below. The index is an arbitrary reference number. Each inspection feature was ranked in priority as of high, medium, low, or non-applicable (H, M, L, NA) from the point of view of responding DOE warehouse operators. The ranking reflects both the frequency of occurrence and the severity with respect to routine inspections and reporting to regulatory agencies.

The indexed list is followed by a prioritized list and a subsystem list.

A4.1.2 Indexed List

Index	Fernald	Los Alamos	Item
1	L	H	Dose rate, gamma
2	M	M	Alpha detector
3	H	H	Pin hole detection
4	H	M	Black drum dents
5	H	H	Rust interpretation
6a	M	M	Liquid detection, puddles on floor
6b	H	H	Liquid detection, on the side of a drum
7a	H	L	Rim and chine dents
7b	M	M	Inspect bolts
8a	H	H	Viewing span, out to 120 degrees
8b	M	M	Viewing span, out to 180 degrees
9	M	M	Pallet inspection
10	L	L	Inside face inspection
11	H	NA	4-high stacks
12	L	NA	5-high stacks
13	H	H	Non-flush aisle ends
14	M	M	Inventory location tracking
15a	L	L	Aisle width, 30 inches
15b	L	L	Aisle width, 26 inches
16	L	L	Outdoor inspection
17	M	M	Simplicity of operator interface
18	H	H	Translucent tents
19	L	H	Inter-facility transport
20	H	H	Automatic recharging
21	L	L	Bulging drums
22	H	H	Tracking defects over time, trend analysis
23	H	H	Bubbling paint
24	H	H	Seam inspection
25	M	H	Deep scratches
26	H	NA	Overhanging drums
27	H	NA	Two or three drums per pallet
28	L	L	110 gallon drums
29	M	M	B25 boxes

30	M	H	Label presence/change
31	M	M	Recording keeping, data basing, archiving
32	H	H	No class 3a lasers
33	H	H	Ignores dust, dirt, extraneous marks
34	H	H	Contamination control (sealed, HEPA filter)
35	H	H	Aisle-end inspection
36	H	NA	Heterogeneous rows
37	L	NA	Heterogeneous stacks
38	M	L	Inspection rate of 12,000 drums/week
39	M	L	Operations with people, equipment, activity

A4.1.3 Prioritized List

The ranking here is arbitrary and simple.

HH is first, with 14 entries.
One H and any lower is second, with 10 entries.
MM is third, with nine entries.
One M and any lower is fourth, with two entries.
LL is sixth, with six entries.
One L and any lower is seventh, with two entries.
No NA-NA items exist.

Index	Fernald	Los Alamos	Item
3	H	H	Pin hole detection
5	H	H	Rust interpretation
6b	H	H	Liquid detection, on the side of a drum
8a	H	H	Viewing span, out to 120 degrees
13	H	H	Non-flush aisle ends
18	H	H	Translucent tents
20	H	H	Automatic recharging
22	H	H	Tracking defects over time, trend analysis
23	H	H	Bubbling paint
24	H	H	Seam inspection
32	H	H	No class 3a lasers
33	H	H	Ignores dust, dirt, extraneous marks
34	H	H	Contamination control (sealed, HEPA filter)
35	H	H	Aisle-end inspection
1	L	H	Dose rate, gamma
4	H	M	Black drum dents
7a	H	L	Rim and chine dents
11	H	NA	4-high stacks
19	L	H	Inter-facility transport
25	M	H	Deep scratches
26	H	NA	Overhanging drums
27	H	NA	Two or three drums per pallet
30	M	H	Label presence/change
36	H	NA	Heterogeneous rows

2	M	M	Alpha detector
6a	M	M	Liquid detection, puddles on floor
7b	M	M	Inspect bolts
8b	M	M	Viewing span, out to 180 degrees
9	M	M	Pallet inspection
14	M	M	Inventory location tracking
17	M	M	Simplicity of operator interface
29	M	M	B25 boxes
31	M	M	Recording keeping, data basing, archiving
38	M	L	Inspection rate of 12,000 drums/week
39	M	L	Operations with people, equipment, activity
10	L	L	Inside face inspection
15a	L	L	Aisle width, 30 inches
15b	L	L	Aisle width, 26 inches
16	L	L	Outdoor inspection
21	L	L	Bulging drums
28	L	L	110 gallon drums
12	L	NA	5-high stacks
37	L	NA	Heterogeneous stacks

A4.1.4 ABCD List

Like other optical inspection methods, the ABCD (Automated Baseline Change Detection) approach to barrel inspection does not depend directly on robot navigation nor sensor manipulators. ABCD does provide absolute change detection. Assuming that the mobile platform can navigate with sufficient agility and position cameras with sufficient precision, then the ABCD system should be able detect all visible changes.

The prioritized list above is further divided below as to what system component best addresses the feature. We assume that the system is composed of the following subsystems:

ABCD Inspection System
Image Understanding System
Navigation and Camera-Positioning System
Data Management System
Other Systems

Within these subsystems, the prioritized ranking is maintained.

Index	Fernald	Los Alamos	Item
ABCD Inspection System			
3	H	H	Pin hole detection
6b	H	H	Liquid detection, on the side of a drum
8a	H	H	Viewing span, out to 120 degrees
18	H	H	Translucent tents
23	H	H	Bubbling paint
24	H	H	Seam inspection
32	H	H	No class 3a lasers
33	H	H	Ignores dust, dirt, extraneous marks
4	H	M	Black drum dents
7a	H	L	Rim and chine dents
25	M	H	Deep scratches
30	M	H	Label presence/change
6a	M	M	Liquid detection, puddles on floor
7b	M	M	Inspect bolts
9	M	M	Pallet inspection
29	M	M	B25 boxes
21	L	L	Bulging drums

Image Understanding System			
5	H	H	Rust interpretation
Navigation and Camera-Positioning System			
13	H	H	Non-flush aisle ends
20	H	H	Automatic recharging
35	H	H	Aisle-end inspection
11	H	NA	4-high stacks
19	L	H	Inter-facility transport
26	H	NA	Overhanging drums
27	H	NA	Two or three drums per pallet
36	H	NA	Heterogeneous rows
8b	M	M	Viewing span, out to 180 degrees
38	M	L	Inspection rate of 12,000 drums/week
39	M	L	Operations with people, equipment, activity
10	L	L	Inside face inspection
15a	L	L	Aisle width, 30 inches
15b	L	L	Aisle width, 26 inches
16	L	L	Outdoor inspection
28	L	L	110 gallon drums
12	L	NA	5-high stacks
37	L	NA	Heterogeneous stacks
Data Management System			
22	H	H	Tracking defects over time, trend analysis
14	M	M	Inventory location tracking
17	M	M	Simplicity of operator interface
31	M	M	Recording keeping, data basing, archiving
Other Systems			
34	H	H	Contamination control (sealed, HEPA filter)
1	L	H	Dose rate, gamma
2	M	M	Alpha detector

A4.2 Warehouse Requirements

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. Although these topics were included by the DOE warehouse operators, the frequency and degree of deviation from expections was worth the trip. The requirements imposed by the warehouse configuration will significantly impact the final version of a mobile platform with respect to navigation and camera positioning.

A4.3 Mobile Platform Requirements

The DOE is pursuing four major programs with respect to waste-barrel inspection. One of these is this ABCD project. Three involve mobile robotic platforms. To the extent that the DOE determines that one of these robotic platforms, or a composite based on these platforms, will be used in barrel inspections, utilizing the platform becomes an operational requirement for the ABCD system.

This is discussed in detail in Attachment 5, Phase 2 Field System Definition. In general, the platforms are similar. While integrating the ABCD system with any other system that was not planned to include it will require some adaptations, the modularity of all systems is good and there appears to be no great risk or difficulty in achieving a fully capable composite system.

A4.4 Conclusions

There are several conclusion that can be made from the above data and analysis. These conclusions could be made even stronger with more warehouse operator input and higher resolution grading choices. The primary conclusion is the last one.

1. The DOE laboratory warehouse operators are surprisingly consistent on the importance of features. As seen from the prioritized list, the only features that had much spread were those having only one high priority and a lower priority. And half of those have to do with warehouse configurations.

2. he high consistency carries over into classification of the features by subsystems.

3. Rust interpretation is one of the highest priority items.

4. Many more aspects of barrel inspection than rust are high priority.

5. Navigation and camera positioning requirements are both numerous and important. Eight out of eighteen requirements have at least one high priority vote and only seven are both low or not applicable.

6. This analysis verifies that the ABCD system is compatible with and critical in meeting DOE ER&WM requirements.

   By emphasizing the ABCD method of inspection with agile and capable navigation and camera positioning, the majority of the operators' highest concerns are addressed.

PHASE 1 TOPICAL REPORT

ATTACHMENT 5

Automated Baseline Change Detection

Task 5 Summary Results

PHASE 1 TOPICAL REPORT

ATTACHMENT 5

Automated Baseline Change Detection

Task 5 Summary Results

Phase 2 Field System Definition

A5.0 General

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

With the opportunity to integrate with the DOE IMSS (Intelligent Mobile Sensor System) project, the scope and character of this ABCD 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.

In particular, by participating in the DOE METC initiated "Bake-off" effort, uniform DOE barrel-inspection requirements are being determined at this time. These requirements cover both the current DOE laboratory warehouse operations requirements and proposed requirements to improve and better perform the inspection process. It is expected that from the bake-off process a final set of mobile platform and inspection requirements and capabilities for a single, modular DOE barrel inspection will be determined.

In so far as the DOE has three significant robotic platform projects, the ABCD project is mainly concerned with providing added-value to each and all of these platforms or to a single or composite platform, depending upon bake-off result. On one hand, the ABCD approach can inspect and find a wide variety of significant changes in barrels if the robotic platform puts inspection cameras in the desired location. With this proviso, the ABCD system should meet all relevant bake-off objectives. On the other hand, the ABCD system imposes some previously unconsidered requirements on the robotic platforms if it is to get the most reliable and most comprehensive results.

Since the robot platform is yet to be defined, it is too early to define and cost a field system that is ABCD capable. However, the bake-off will very well serve as the practical trade study for meeting DOE requirements. At this point in time ABCD is determining what DOE requirements it needs to address, which will be met by other projects, and what requirements ABCD will impose on the other projects and on the bake-off.

We summarize the results of this task in the following sections: "Bake-off" Technical Criteria, Mobile Platform Assessments, ABCD Requirements, and Conclusions.

A5.1 "Bake-off" Technical Criteria

The following are the current requirements planned for the DOE barrel-inspection "bake-off". They address Required Elements, Key Performance Attributes, Possibly Required Elements, and Optional Elements. These criteria represent a consensus of DOE representatives and contractors.

A.5.1.1 Required Elements

Autonomous Navigation
- Fixed, known facility

Reliable obstacle detection and avoidance
Ability to store suspect images
Barcode reading capability
- Drum ID

Rust detection
55 gallon drums
Homogeneous by stack
- Affects aisle width by overlap

3-high stacks
- 4-high for SWAMI clearance

Inventory Coverage accountability
36" aisle width

A5.1.2 Key Performance Attributes

- Throughput
  - 10-12 K barrels / week
- Cost
  - Account for labor savings, if any
- Leaker rate reduction
  - Trend analysis capability
  - Real benefit to customer
- Environmental robustness
  - Temperature
  - Humidity
  - Puddles
  - Fluorescent lighting
  - Dust
- False positives and negatives minimized
- Drum inspection accountability
- Aisle width, length, complexity
  - Tees, dead ends, herring bone
- Safety systems reliability
  - Emergency stops
  - OSHA issues
- Overall reliability
- Human factors design

A5.1.3 Possibly Required Elements (Status TBD)

- Streak detection
- Blister detection
- Dent detection
- Tilt detection
- Bulge detection
- Minimum feature size
  - Surface area clearance
    - Angle off centerline
- Pallet inspection
- Bolt inspection

A5.1.5 Optional Elements

- Feature recategorization and learning
- Inventory checking
    - Out-of-place drums
    - Missing drums
- 100% documentation
- Robust performance
    - Drum column misalignment
        - Lateral
        - Depth
    - Heterogeneous stacks
    - Missing or extra pallets on a row
    - Dead-end aisles
    - All lighting conditions
        - Bright to dark
    - Stray markings on drums
- 55, 85, 100 gallon drums, B-25 boxes
- 4-high stacks
- Outdoor operation
    - For transitions and inspection
- Environmental sensing
    - Floor radiation
    - Ambient radiation
    - Temperature, humidity
    - Lighting
    - Puddles

A5.2 Mobile Platform Assessment

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). Since the merger the two companies have been closely collaborating and integrating the two projects. With unrestricted intercompany transfer of labor and data, this has improved the cost-effectiveness of both projects.

Further, after the project began and the company mergers, with explicit DOE support, 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.

Since integrating the ABCD and IMSS projects and since the DOE METC has taken a lead role in determining DOE operational requirements for barrel inspection, the ABCD project is no longer planning to design, build, develop, and field its own mobile platform. In so far as the DOE has three significant robotic platform projects, the ABCD project is mainly concerned with providing added-value to each and all of these platforms or to a single or composite platform, depending upon bake-off result.

Toward this objective, the ABCD project has attended each of the Phase 2 demonstrations of DOE's barrel-inspection projects. Each individual platform was observed to assess capabilities and limitations that could impose unique requirements on ABCD beyond DOE operational requirements.

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

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

A5.3 ABCD Requirements

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 1995 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.

A5.4 Conclusions

The ABCD system can add significantly to the capabilities of the IMSS, ARIES, and SWAMI barrel inspection systems. Many of these capabilities are required by DOE warehouse operators, while others are highly desirable and provide a much more effective inspection system.

The DOE is in the process of consolidating its mobile platform and inspection requirements with respect to IMSS, ARIES, and SWAMI. It is not yet clear how to integrate ABCD with these systems without imposing added burden to each of them while trying to meet their initial objectives. Following the bake-off, with one existing platform or a new composite platform, an initial set of field system requirements will defined. ABCD imposed requirements on the robotic platform will be included at that time.

Meanwhile, ABCD will continue to concentrate on refining change detection and use the IMSS for robotic-platform integration. This will provide the DOE with the most cost-effective approach to achieve the full operational capabilities desired by DOE warehouse operators. All these capabilities can only be achieved with the ABCD project supplementing other DOE barrel-inspection projects.