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Facility and Component Inspection Technology Concepts: Potential Use in U.S. Army Maintenance Management

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Army installation Directorates of Engineering and Housing (DEHs) are responsible for managing a huge inventory of constructed facilities that support the military mission. This task has grown increasingly complex as many facilities are approaching or have reached the end of their useful lives and thus require ever an increasing share of the already limited maintenance and repair (M&R) budget. Condition assessment through periodic facility inspection has been long recognized as a preferred means for deficiency identification so that work can be planned and scheduled properly before neglect accelerates into major degradation and requires costly repair. However, at most installations, the inspection resources are very limited, resulting in a less than adequate program.

At the center of this management issue is how best to allocate limited M&R funds to ensure the most cost-effective dispersal of resources. Most installations do not have ready access to the different types of data needed to support effective decisions.

Improved inspection technology has been proposed as a way to both offset reductions in personnel and provide information critical to decision support. The U.S. Army Construction Engineering Research Laboratory (USACERL) investigated new facility and component inspection technologies for potential use in the Army. However, surveys of field personnel revealed that improved inspection techniques alone will do little to facilitate the management process. Due to this finding, USACERL widened the scope of this study to investigate technologies that could serve the entire management process including facility imaging, image storage, and image processing. A conceptual approach was developed which includes both optical and infrared imaging for facility inspection.

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Army installation Directorates of Engineering and Housing (DEHs) are responsible for managing a huge inventory of constructed facilities that support the military mission. This task has grown increasingly complex as many facilities are approaching or have reached the end of their useful lives and thus require ever an increasing share of the already limited maintenance and repair (M&R) budget. Condition assessment through periodic facility inspection has been long recognized as a preferred means for deficiency identification so that work may be properly planned and scheduled before neglect accelerates into major degradation and requires costly repair. However, at most installations, the inspection resources are very limited, resulting in a less than adequate program.

At the center of this management issue is how best to allocate limited M&R funds to ensure the most cost-effective dispersal of resources. Managers need facility information to help in the decision-making process. However, most installations do not have ready access to the different types of data

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needed to support effective decisions. In addition, some installations are forced to appropriate most of their budget to the most immediate M&R needs rather than invest in long-range planning.

Improved inspection technology has been proposed as a way to both offset reductions in personnel and provide information critical to decision support. The U.S. Army Construction Engineering Research Laboratory (USACERL) was asked to investigate new facility and component inspection technologies for potential use in the Army. However, surveys of field personnel revealed that improved inspection techniques alone will do little to facilitate the management process. Due to this finding, USACERL widened the scope of this study to investigate technologies that could serve the entire management process.

Facility imaging, image storage, and image processing is a generic area of technology which appears to hold much promise for the task of facility managers. A conceptual approach has been developed which includes both optical and infrared imaging for facility inspection. The conceptual system is envisioned as interacting with the mini/micro Integrated Facilities System (IFS-M) and various engineered management systems under development. This capability will allow managers to access the full spectrum of data needed for effective decision-making.

FOREWORD

This research was conducted for the U.S. Army Engineering and Housing Support Agency (USAEHSC) under Project 4A162734AT41, "Military Facilities Engineering Technology"; Task C, "Operation, Management, and Repair"; Work Unit 058, "Facilities Maintenance Inspection Technology and Repair of Materials." The work was conducted by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (USACERL). The USAEHSC Technical Monitor was Robert Williams, CEHSC-FB-P. His support is very much appreciated.

Dr. Kenneth Maser is a research associate and Timothy Tonyan is a graduate student with the Civil Engineering Department at the Massachusetts Institute of Technology (MIT). The contributions of Robert Pugh, David Brown, Eric Lawson, and Susan Wagers of USACERL and Samer Madanat of MIT are gratefully acknowledged. The USACERL technical editor was Dana Finney, Information Management Office.

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Dr. R. Quattrone is Chief, USACERL-EM. COL Carl O. Magnell is Commander and Director of USACERL, and Dr. L. R. Shaffer is Technical Director.

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FACILITY AND COMPONENT INSPECTION TECHNOLOGY CONCEPTS: POTENTIAL USE IN U.S. ARMY MAINTENANCE MANAGEMENT

1 INTRODUCTION

Background

The U.S. Army owns and operates a huge, diverse inventory of constructed facilities. This inventory ranges from simple "temporary" wooden barracks built during World War II to highly sophisticated research and medical complexes. These facilities are exposed to every imaginable environmental and weather condition in locations ranging from urban centers to the most remote deserts. Individual facilities are grouped into installations. An Army installation may consist of a small number of simple facilities with only loosely related functions or, at the other extreme, it may have thousands of facilities with complex interrelationships that must meet the civil and environmental needs of a population equal to a small city.

Clearly, managing these facilities is a challenge. Effective management requires an understanding of the facilities inventory, the component parts and their interrelationships, and the impact of their performance on the installation mission. Understanding the facilities requires knowledge of their performance and physical condition. Performance is the measure of how well a facility is serving its intended function. Condition is the measure of the physical characteristics (e.g., deterioration) of individual components. Performance evaluation and condition assessment of facilities entail collecting necessary data that serve as a basis for analyzing management priorities. Effective facilities management requires technology to capture these data and support the information flow required for decision-making.

Several specific needs are related to this area. The first is to effectively assess the physical condition of Army facilities and clearly identify the action required to maintain these conditions at a desired level. There is a growing realization among Army facilities managers at all levels that a high percentage of facilities have reached or exceeded their useful lives. This fact, and the associated maintenance problems, have forced a new awareness of the need for component and facility inspections, and for efficient maintenance management. The fact that annual budgets for maintenance and the backlog of maintenance and repair (BMAR) often exceed those for new construction has also placed new emphasis on this need.

A second need is to offset reductions in maintenance and inspection personnel with improved inspection methods and technologies. Recent reductions in field staff and increasing reliance on outside contractors to perform maintenance functions have created the need for more inspections, with less manpower to perform them.

Finally, there is a need to use inspection information to support decision-making at the component, facility, and installation levels. Inspection information must be collected and interpreted with respect to its value as a decision tool. In other words, there is a need to define technology capable of translating accurate facility condition information into efficient maintenance practice.

Objective

The overall objective of this work is to identify technologies that could improve the Army's ability to manage its facilities. The specific objective of this study is to identify technologies that will

improve the Army's ability to assess the physical condition of its facilities. A secondary objective is to identify technologies that will enable the Army to translate the knowledge of facility condition into efficient maintenance policy and practice.

Approach

Initially, a research approach was defined as follows:

1. Identify the facility components for which the most maintenance and repair (M&R) money is spent and identify inspection information that could reduce these expenditures through early defect identification and correction.

2. Identify the facility components representing the greatest risk of failure due to lack of adequate inspection information (risk defined in terms of both human safety and economics).

3. Identify current Army maintenance inspection procedures, quantify inspection costs, and propose technological improvements to reduce cost and improve information.

4. Identify emerging inspection technologies that will have Army condition assessment applications in 1 to 5 years. Identify how these technologies can be applied to current and future inspection needs.

5. Recommend research for developing new inspection technologies in areas where inspection information needs have been identified, but the technology has not been developed adequately.

A phased approach was proposed, beginning with a broad overview of maintenance inspection needs, then narrowing these needs, selecting technologies to meet these needs, and developing a future plan.

In fact, the actual research did not proceed exactly according to this plan. Review of Army Integrated Facilities System (IFS) data bases did not reveal specific high-maintenance, high-priority components for further focus as suggested in items (1) and (2) above. Telephone and written surveys conducted to augment limitations of the data base failed to reveal a consensus of high-priority items. Although several different facility components such as roofing and painting were often cited as being critical M&R items and the recipients of large M&R expenditures, no small group of components was cited as overwhelming candidates for potential M&R cost savings or safety risk reduction through better inspection procedures (e.g., 80 percent of the M&R expenditures devoted to 20 percent of the facility components). Rather, the need was found to be much more broad-based and applicable to virtually the entire range of facility components. Also, these surveys revealed maintenance concerns beyond the need for component inspection. As a result, the study adopted a broader view of the entire maintenance process, and maintenance technology was considered in this context.

Scope

This project included a review of existing Army and industry facilities maintenance practices; a review and assessment of inspection technologies and their potential value for use within the Army; and recommendations for future development. The domain of facilities under consideration included constructed facilities found within Army installations.

More specifically, this report:

1. Describes the results of reviewing maintenance practices at military installations.

2. Presents a perspective on maintenance information needs and describes a variety of technologies available to meet these needs.

3. Reviews these technologies and recommends the automated imaging concept as one that would address the most significant needs.

4. Presents and describes the concept of automated imaging.

5. Describes the development and implementation of automated imaging.

Mode of Technology Transfer

Information in this report will serve as background for investigating some existing inspection technologies and will point to further research needs in the automated imaging area. In addition, information is provided on how the Directorate of Engineering and Housing (DEH) should and actually does perform the task of work identification. Researchers working on Engineered Management Systems (EMSs) also can use this information to further develop systems and incorporate state-of-the-art data collection procedures.

Some of the technology presented is currently available commercially and has been used at certain installations by contractors or in-house staff. These applications should continue, where practical, and this report will serve to inform DEHs and Major Commands (MACOMs) about the available technologies.

2 CURRENT MAINTENANCE PRACTICE AT ARMY INSTALLATIONS

Information Gathering

To assess current Army maintenance inspection practices, a combination of written survey, telephone survey, and site visits was used. The written surveys were sent to virtually all installations via the appropriate MACOM. Over 100 responses were received. Telephone interviews followed to selected sites to gather additional information. At appropriate times throughout the project, a few sites were visited so that personal interviews could be conducted and the researchers could gain firsthand knowledge of the facility inspection and management process. Appendix A lists the people interviewed both by telephone and onsite. The results of the telephone and written surveys are compiled in Appendix B. Those installations responding to the written survey are also listed in Appendix B.

The focus of the information gathering and surveys was to establish existing inspection practices and determine how inspection information is used. A second objective was to identify which facilities and components require the most maintenance and which components have maintenance requirements that could be reduced by improved inspection information. The ultimate goal was to identify inspection information needs for key components and to understand how this information should be incorporated within the overall maintenance management environment.

Maintenance Organizations and Operations

Maintenance is the responsibility of installation DEHs,* whose mission, as defined by Army regulations, is to plan, direct, supervise and coordinate all installation facilities engineering activities. This task includes the design, minor construction, operation, and maintenance of all real property (buildings, grounds, railroads, surfaced areas, utility plants, and systems). Fire prevention, real estate management, and the organization of maintenance equipment and services are also key responsibilities of the DEH.[1]

This study is concerned primarily with that area defined as M&R of all real property. To fulfill its mission efficiently, the DEH is structured as a hierarchy, with responsibility divided into several major functional areas (Figures 1 and 2).[2] Each of these areas is divided into several branches along functional or operational lines. Divisions responsible for maintenance of facilities that fall within the domain of this study are Engineer Resources Management, Building and Grounds, Utilities Division, and the Hospital Support Division. Typical organizational charts for these elements are shown in Figures 2 through 5. Variations, however, are common.

Engineer Resources Management (ERM) is responsible for programming, coordinating, and scheduling engineering resources for work to be done by installation forces. Maintenance work reception and scheduling are handled by ERM in coordination with other functional areas. Work reception deals with short-term service order work as well as longer range planning. Periodic inspection of

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*Throughout this report, reference is made to the DEH, but it is intended to encompass Facility Engineers (FEs) and Directorates of Installation Support (DIS) as appropriate.

[1] Army Regulation (AR) 5-3, *Installation Management and Organization* (Headquarters, Department of the Army [HQDA], 1986); Department of the Army Pamphlet (DA Pam) 570-551, *Staffing Guide for U.S. Garrisons* (HQDA, December 8, 1976).

[2] AR 420-10, *Facilities Engineering General Provisions, Organization Function, and Personnel* (HQDA, 1981); AR 5-3.

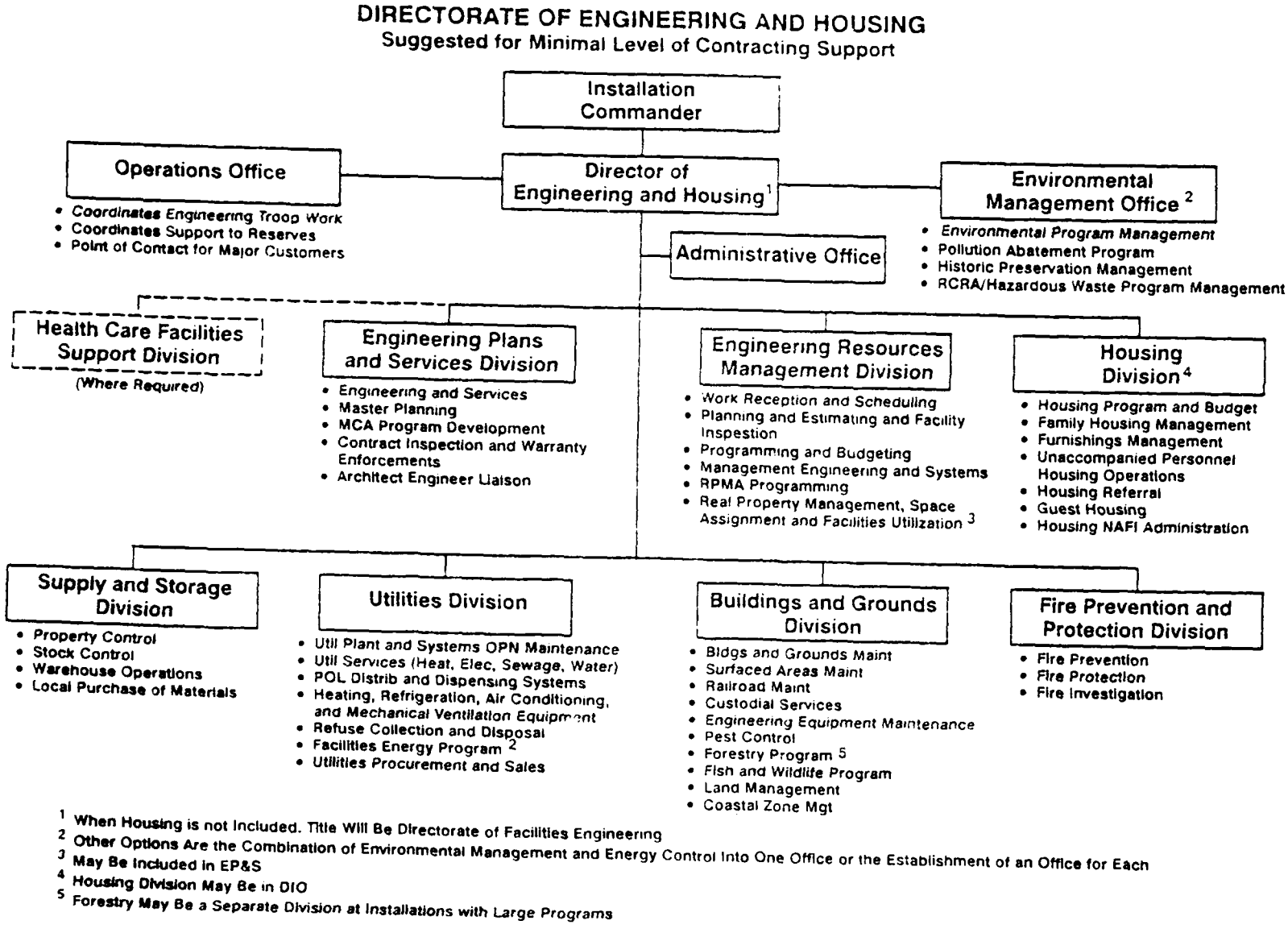

Figure 1. Directorate of Engineering and Housing organizational structure. (Source: AR 420-10.)

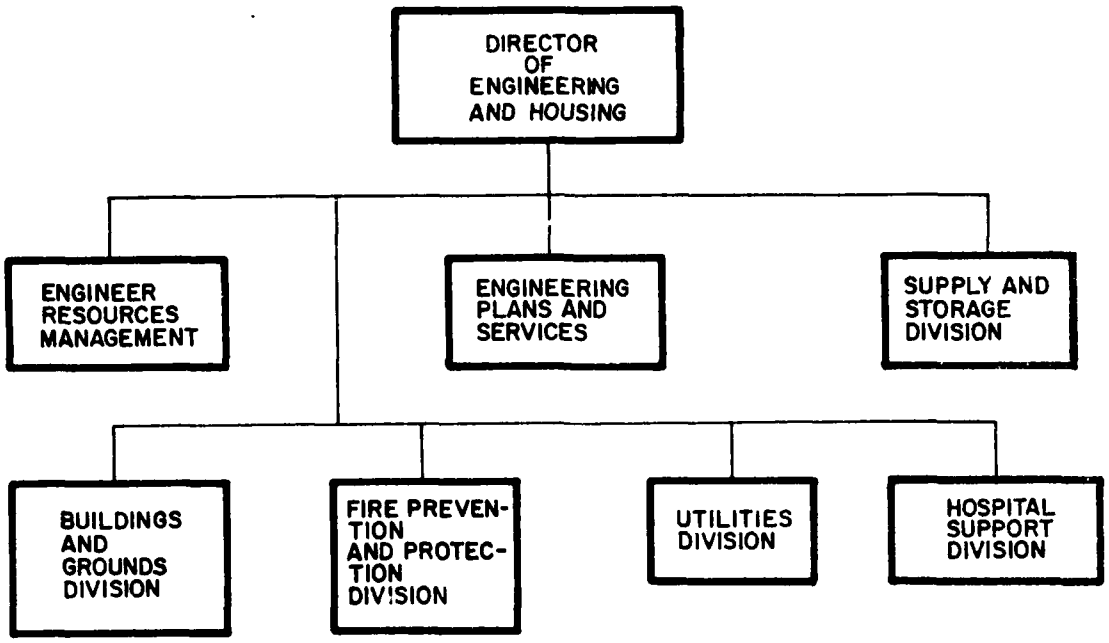

Figure 2. **Directorate of Engineering and Housing (contractor performs non-Governmental functions).** (Source: AR 5-3.)

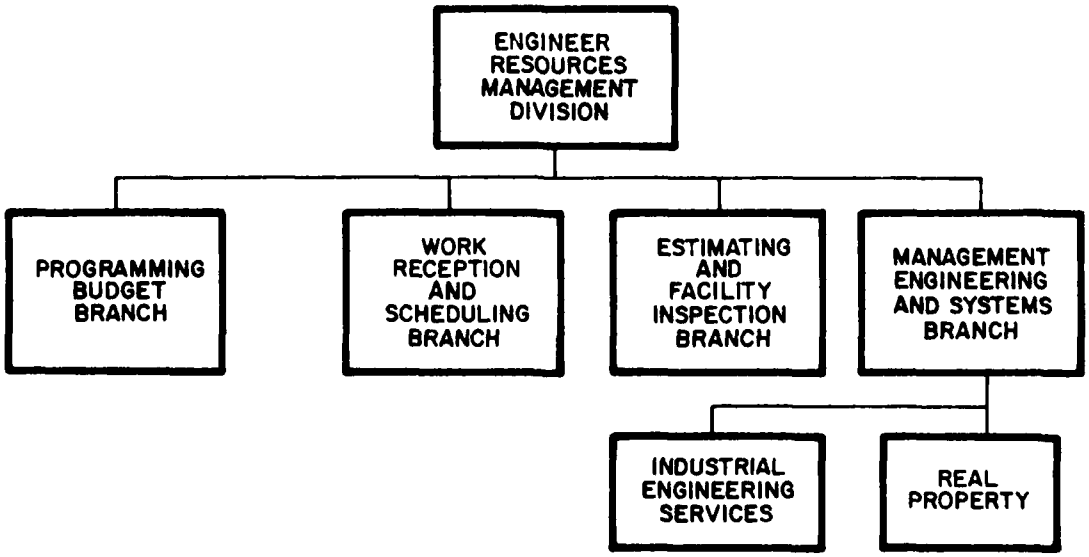

Figure 3. Engineer Resources Management Division.

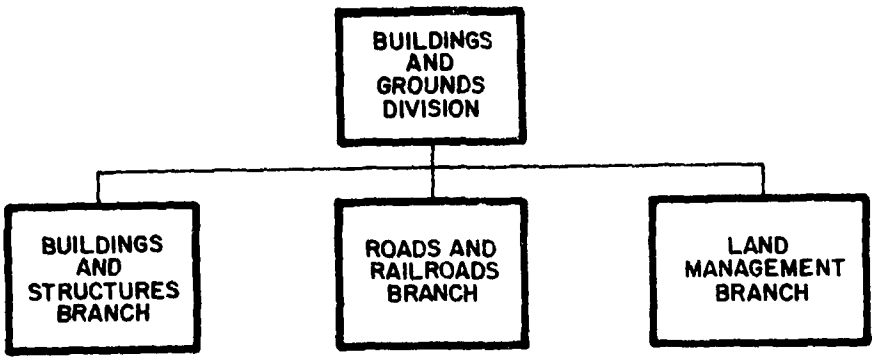

Figure 4. Buildings and Grounds Division.

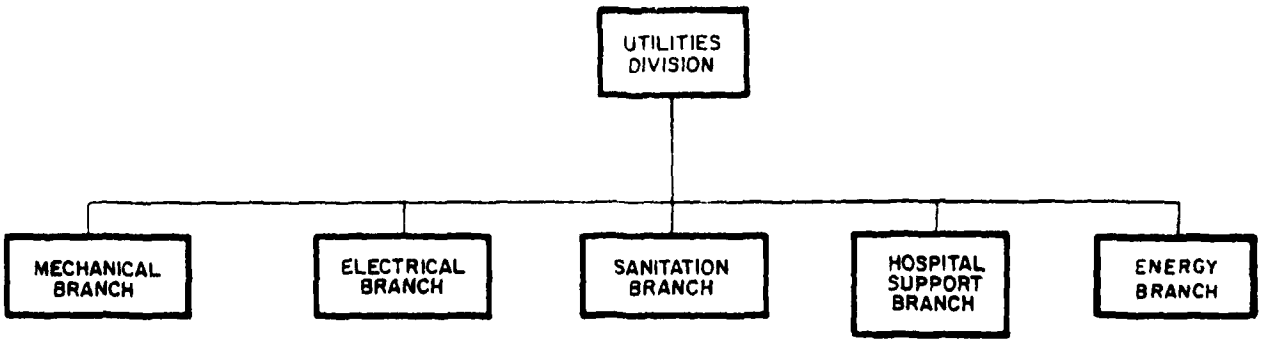

Figure 5. Utilities Division.

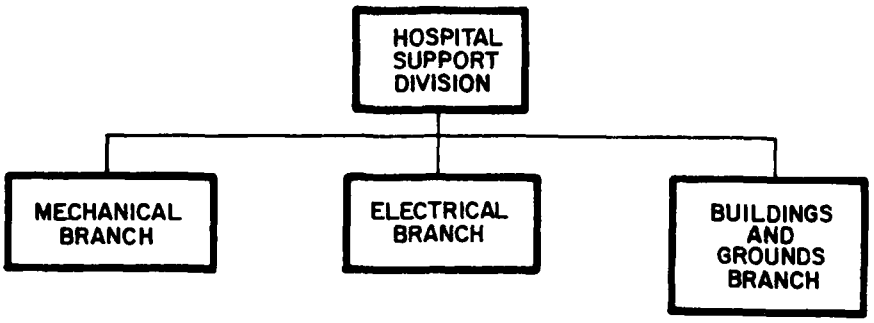

Figure 6. Hospital Support Division.

facilities and components is also a function of the ERM.[3] The purpose of these inspections is to assess the overall condition of a facility and determine long-range M&R requirements.

The Buildings and Grounds, Utilities, and Hospital Support Divisions are operations-oriented. Each is responsible for supervising and coordinating the operation and M&R of the real property under its control.[4] This operations and maintenance (O&M) responsibility translates into two key functions: (1) performance of day-to-service orders and unscheduled M&R work, and (2) preventive maintenance. Buildings and Grounds, Utilities, and Hospital Support are each responsible for supporting a program of preventive maintenance appropriate for the facilities under their control. Thus, the "shops" in each of these divisions must both handle service order calls and provide an ongoing program of inspection to be done during preventive maintenance and M&R activities for a variety of facilities, components, and equipment.

Types of Maintenance

The previous section described two types of maintenance inspections the DEH performs: facility component inspections done by the ERM on a periodic basis and inspections done during preventive maintenance activities at the operations level. To understand the informational requirements of these inspections, it is first necessary to describe the type and nature of maintenance activities conducted. These activities are classified as service orders, work requests, and preventive maintenance, as described below.

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[3]DA Pam 570-551.
[4]DA Pam 570-551.

The ERM manages services orders and work requests. A service order is a specific item of maintenance or repair a customer requests that can be handled by shop or service personnel as a routine or short-term action. Cost and time thresholds are typically established to separate service orders from reception deals with short-term service order work as well as longer range planning. Periodic larger types of repair. Typical service orders involve repair of leaking faucets, changing belts in air handlers, and repairing broken glass in a window. Most service orders are requests that can be handled in a working day or less and require labor and materials costing less than $1000. Service order requests are usually received by the work reception desk at ERM and passed to the shops or maintenance contractor. These requests are submitted by customers (i.e., facility users) or by DEH personnel such as preventive maintenance crews and component inspectors who have identified small-scale repair needs. The shop or contractor schedules and does the work. It should be noted that references to "routine," "day-to-day," and "small-scale" do not imply that this work is nonessential. In fact, a considerable amount of service order work by its very nature is emergency repair, assuming a very high priority.

Work requests are handled by ERM and are larger and more complex. These work requests deal with repair or maintenance projects, as well as additions and deletions, that involve considerable planning, time, and expense. These requests appear in yearly and longer range budgets and work plans. Priorities for such projects are established at the Directorate level, in coordination with ERM and other functional areas. Work requests may be submitted by customers on the installation or established by the ERM as a result of its facility inspection function. Work requests involve items such as replacing roofs, resurfacing roads, and replacing obsolete electrical systems.

The responsibility for preventive maintenance (PM) work is assigned to the individual branches. PM programs vary greatly among installations and among the branches on an installation. The level of PM being conducted is largely a function of the branch management's commitment to it. Some branches operate with separate crews for service orders and PM. In this scenario, the PM crews regularly cycle through the facilities where they are responsible for performing predetermined scheduled maintenance tasks on key equipment. A variation of this approach is to allocate a predetermined percentage of a crew's time to PM, with the remaining time going to service order work. In this second scenario, the backlog and urgency of service order work often leaves little to no remaining resources for PM.

Survey and interview results indicate that, in practice, neither of the above two PM systems is widely employed. Many installations do not have formal PM crews or time allotted specifically to PM. For these installations, the best case is that PM is done in "slack times" when service order work is slow. An example would be mechanical crews completing PM on boilers and steam equipment in the summer, or air-conditioning crews working on the units during the winter. This system can and does work well, given adequate manpower and seasonal variations in service work demands. It appears to be most successful on relatively small installations. On larger installations with complex facilities, large populations, and overextended maintenance personnel, this system is clearly not working. At these installations, frustration has been expressed over the failure to implement an effective PM program.

Facility and Component Inspections

As described earlier, maintenance inspections are now done at two different levels: the ERM and the "shop." Facility inspection is a primary responsibility of the ERM. It involves evaluating the condition of a facility's components and identifying needed repairs. Scoping estimates for the repairs are submitted to the planning sections within the DEH for prioritization and preparation of work plans. Army guidance recommends that these facility inspections take place on a periodic basis for all facilities on an installation (every 3 years for all facilities and components and every 12 months for

roof trusses).[5] Component inspectors typically work as a team with a structural, mechanical, and electrical inspector evaluating a facility in detail. Sometimes one inspector will cover more than one trade (e.g., electrical and mechanical). Visual analysis is the primary inspection method, with results documented in written reports. Structural inspectors typically use handtools such as a flashlight and screwdriver. Electrical inspectors normally use these tools as well as side cutters, an amp probe, and a voltage tester.

Traditionally, most components are condition-coded in one of three categories: good (C1), marginal (C2), or unsatisfactory (C3). Facilities and/or components that have developed EMSs use a 0 to 100 condition index for condition coding (discussed in the next chapter). M&R needs identified during a facility inspection are documented and reported.[6] Minor repairs are reported as service orders and handled as such. More extensive M&R requirements are documented appropriately as part of the formal work planning process. The action includes preparing "scoping estimates" of time and cost to perform the work. These work requests are then used to develop an annual work plan, budget requests, and establish other requirements such as the BMAR.[7]

At the "shop" level, the operational divisions (Building and Grounds, Utilities, and Hospital Support) perform periodic inspections as a part of their PM and repair functions. These tasks are operations-based and results are primarily used for shop maintenance activity planning. DEH management often asks operational division management to provide input on long-range work requirements, as well. It is the operational division personnel who are most intimately aware of the actual condition of facilities and components on a day-to-day basis. It is also these persons who currently generate the most requests for additional inspection technologies to be applied to evaluate specific components. Visual analysis is the primary inspection method. Nondestructive testing and remote sensing methods such as infrared thermography, video imaging, and vibration analysis have been employed on a limited basis for specialized applications. Some specific examples are infrared thermography to detect the presence of moisture in built-up roofs, video imaging inside sewer and storm drain lines to identify blockages, and vibration analysis to determine wear on bearings in motors.

Current Technology for Maintenance Management

To meet the needs of the complex maintenance management tasks discussed above, the Army has developed and continues to work on a number of information and maintenance management systems. These systems are introduced here, with a detailed discussion later in the report. As background, it should be noted that the DEH at each Army installation is allowed to select its own management structure and style. Thus, the mechanisms and procedures for a given installation may vary somewhat from the description above. Whether maintenance and service orders are completed by DEH personnel or outside contractors also impacts how the DEH is structured. However, the fundamental roles of the different divisions, their relationships to one another, the kinds of work they perform, and the type of information they use are very similar across all installations.

To gain a perspective on the size and complexity of the responsibilities outlined for these divisions, consider the following figures. Many Army installations have DEH annual budgets in excess of $30 million to manage more than $1 billion in real property. This translates into an inventory of facilities numbering in the thousands, with subsystems and components numbering in the millions. It

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[5] *Integrated Facilities System (IFS) Real Property Maintenance Activity (RPMA) Users Manual*, Vol IV (Facilities Engineering Support Agency [FESA], September 1979).
[6] *Real Property Maintenance Activity (RPMA) Component Inspector's Handbook* (U.S. Army Facilities Engineering Support Agency [FESA], May 1979).
[7] *IFS RPMA Users Manual*, Vol IV.

is not unusual to have 60,000 service calls annually at large installations. These service calls must be assigned a priority and their importance weighed against the PM requirements that shop personnel must perform. Decisions on which facilities and which components within the facilities to inspect must be made by component inspectors. For each decision and action taken, documentation is required.

Due to the large quantity of information to be managed, most installations have adopted automated maintenance management tools for specific applications. Until recently, most of these automation efforts have been centered in the financial and administrative areas, and have been operations-oriented. For example, the Integrated Facilities System (IFS) is an Army-wide system designed to assist the DEH with (1) facility accounting and reporting, (2) day-to-day management of facilities (O&M), and (3) resource management functions.[8] It was initially designed as a mainframe-computer-based management information system (IFS-I) and is now being modified to operate in a minicomputer environment (IFS-M). The mainframe IFS-I has not seen wide implementation at the maintenance management and operations level due to several factors. Batch processing input requirements, lag time in receiving processed information, and difficulty in computer interfacing at several levels have contributed to limited application for actual maintenance practice. Another key problem in implementing IFS-I as a maintenance tool is the lack of a reliable and accessible facilities inventory at the maintenance operations level. The result has been piecemeal implementation of IFS-I, with most applications oriented to the financial and accounting aspects of the system. IFS-M is discussed in more detail in the next chapter.

To meet the need for automation, many other systems have been employed at the maintenance level. Some installations are highly automated, with detailed data bases of a facilities inventory serving as the foundation for sophisticated maintenance management programs (e.g., Forts Irwin, CA, and Riley, KS). Other installations (e.g., Forts Ord, CA,[9] and Stewart, GA) keep records of service orders, work requests, and PM work on microcomputer systems using software such as Lotus 1-2-3 (Lotus Development Corp.) and DBase III (Ashton-Tate). Component-specific maintenance management systems such as PAVER[10] have been implemented on some installations. PAVER, originally developed for mainframe application with each installation having its own data base maintained locally but administered by the U.S. Army Engineering and Housing Support Center (USAEHSC), is now being adapted to the microcomputer environment existing on the individual installations. A generalized component and facility maintenance management concept based on EMSs is currently being developed using PAVER as a model. The abundance of different systems in use and under development, coupled with the need for numerous departments and divisions to share information, suggest a need to integrate these management systems. Efforts are currently underway to at least partially integrate component EMSs into expanded facility EMSs and to integrate IFS-M with EMSs. The U.S. Army Construction Engineering Research Laboratory (USACERL) is working on the EMS integration problem; USACERL and USAEHSC are working jointly to solve the IFS/EMS integration problem. IFS-M and EMS are discussed at length in Chapter 3.

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[8] *Functional Description, Prototype Development Methodology, Integrated Facilities System, Mini/Micro (IFS-M)*, Executive Summary (Internal FESA document, 1987).

[9] "Engineering Study Produces Computerized Facility Management Program at Army Base," *Government Product News* (January 1987), p 44.

[10] M. Y. Shahin and S. D. Kohn, *Overview of the "PAVER" Pavement Management System and Economic Analysis of Field Implementing the "PAVER" Pavement Management System*, Technical Report M-310/ADA116311 (U.S. Army Construction Engineering Research Laboratory [USACERL], March 1982); M. Y. Shahin, and S. D. Kohn, *Pavement Maintenance Management for Roads and Parking Lots*, Technical Report M-294/ADA110296 (USACERL, October 1981).

Also needed is a way to integrate inspection data into the automated management systems. Currently, most data collection and entry are manual. The issue of automated data entry and data base integration will become more significant with the development of automated data collection technology, as will be discussed later in this report.

Additional Results of Written and Telephone Surveys

A considerable amount of the general information presented above was obtained through the surveys and interviews noted earlier. Some additional points brought to light in these surveys are notable.

On the subject of component inspection, it was found from a statistical analysis of the written survey data (Appendix B) that there is no correlation between maintenance and inspection expenditures. In contrast, maintenance expenditures, total DEH budget, and value of the capital plant were highly correlated. This pattern suggests that the DEH budget is set by the value of the capital plant, and that the maintenance budget is set as a fixed percentage of the DEH budget. It also suggests that inspections are not programmed based on the extent of the capital plant, nor do they bear any relationship to the level of maintenance activity. The meaning of these numbers was confirmed in telephone conversations. In general, inspection is an activity which is done if and when time and manpower are available after other maintenance activities. Several installations reported inadequate resources to maintain facilities that are in obvious need of repair. In these situations, use of resources for inspecting components to detect less obvious conditions would be ridiculous. The large proportion of maintenance devoted to service order work (about 40 percent) also explains the lack of connection between inspection and maintenance.

A second revelation in the surveys was a reluctance on the part of some facility managers to adopt mainframe PAVER, despite its high visibility. This reluctance is due, in part, to a perception of high implementation and operating costs. Another perception is the need for special training and for training manuals to properly operate the system. These perceptions, particularly the high costs, appear to be the prime factors in preventing rapid PAVER implementation. Interviews with maintenance managers from nonmilitary organizations confirmed those same perceptions. Even though more than 60 installations and 100 cities have adopted PAVER, the numbers should be much higher.

Although the one-time implementation cost (documented in a PAVER economic study)[11] at any given location may be several thousand dollars, in many cases, this cost represents only a fraction of the total pavement maintenance budget. The U.S. Army Training and Doctrine Command (TRADOC) estimates the implementation costs at less than 1 percent of the maintenance budget. To help overcome this cost problem at the local level, both the U.S. Army Forces Command (FORSCOM) and TRADOC have centrally funded the implementations at many installations.

The issues of training and operational costs have been addressed through the development of Micro PAVER. Operating costs have been greatly reduced and the overall system is much easier to operate than mainframe PAVER.

However, although many of the PAVER cost and use problems have been overcome, some installations are still reluctant to invest the long-term personnel resources required to implement, understand, operate, and maintain a management system such as PAVER. This attitude clearly represents a major institutional hurdle to the implementation and use of EMSs.

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[11] M. Y. Shahin and S. D. Kohn (March 1982).

General Observations

The current lack of an integrated data base containing facility maintenance information has direct impact on actual maintenance practice. At the operations level, a strong emphasis is placed on service order work and the immediate solution of urgent problems. PM tasks required on a scheduled basis frequently suffer a lack of manpower and are not completed due to shop personnel being tied up full time on service orders. Although some installations would take exception to this observation, interviews and surveys confirm that most of the maintenance management personnel contacted feel that they spend less time on planned PM than they would like. This situation is due in large part to the number and urgency of service order and work requests they must complete with limited personnel. Therefore, at the operating division level, there is limited opportunity to obtain or use component inspection data. At the ERM inspection level, however, a strong emphasis on "work identification" serves to motivate component inspections. Often, the result is "condition assessments" to prepare scoping estimates rather than a detailed inspection of the facility's physical condition The outcome is a situation in which operations-level staff have little use for the condition assessment information generated by the ERM, while condition assessments are done by the ERM without full benefit of the detailed operating characteristics of individual components that the shop personnel have.

Based on interviews and surveys, some general observations can be made about current maintenance management practice at U.S. Army installations:

1. Facility maintenance inspection practices vary widely among installations. Some installations have a team of full-time ERM facility component inspectors; others do no periodic component inspections at all.

2. Numerous large installations reported having no PM programs in place, whereas several relatively small installations reported well staffed and highly developed PM programs.

3. DEHs would like to conduct more maintenance inspections but feel they do not have adequate manpower or money to do so. Personal interviews and survey responses consistently revealed this desire. These resource problems are a reality and not just a perception of those who must comply with component inspection requirements. Additional money could overcome manpower shortages through contractual efforts.

4. A high percentage (above 40 percent) of the maintenance effort involves "service order" type work. Thus, maintenance is reactive rather than proactive. One shop foreman interviewed estimated that 80 percent of his staff's time is spent on service orders. Other survey responses were in that same range. The desired level was stated to be in the range of 20 percent.

5. There is a general consensus among maintenance staff that they need more information about their facilities' conditions than is currently accessible. A clear example of this need is the recent roof collapse on a warehouse at one installation. This catastrophic outcome could have been prevented through timely inspection and maintenance. Quoting an ERM manager's survey response: "We need to make smarter decisions. Improved inspections should help us make better decisions." This sentiment is common among DEH staff at all levels.

6. Objective justification of work projects undertaken or under consideration is an ongoing concern at the management level. Interviews with one base indicated that an Army Audit Agency (AAA) report revealed the need for improved quantitative physical evidence to demonstrate the need for maintenance actions taken. Other survey respondents communicated a similar need.

7. Facility inspections are often contracted to outside consulting firms. There is little standardization of specifications for these inspection services. A major installation has recently prepared specifications for these services with the help of the USACE District Office.

8. With the exception of local PAVER implementations, there is no facility inventory and condition data base at the maintenance management level (engineering resource management and shop foreman levels) being used in coordination with inspection practice. Shop foremen consistently reported that they maintain their own partial inventory of facilities and equipment, or that no reliable inventory exists at the level of detail useful for the shops. In addition, when installation personnel were asked to provide detailed service order data for analysis, it was found that considerable effort was necessary for the retrieval. This highlights the lack of an easily accessible condition and maintenance information data base. The further development of the family of EMSs and their integration into IFS-M should help to rectify this problem.

These findings suggest, among other things, that the Army installation maintenance environment is driven by immediate necessities. In this environment, inspection data and management systems have low priority. Therefore, improved technology for component inspection alone would be of little overall value. Consequently, a broader look at maintenance information needs was suggested as a means of identifying appropriate directions for technological development. Thus, the objective of this study shifted somewhat to accommodate a wider scope. The rest of this report focuses on the technologies and methods with potential for improving the facilities maintenance management approach at Army installations.

3 TECHNOLOGY FOR MAINTENANCE INFORMATION REQUIREMENTS

Perspective on the Value of New Inspection Tools

The observations from the preceding section provided an important perspective on the value of new inspection tools. New tools at the component level are of value only if the information gathered can be used effectively. It is difficult to extract maintenance benefit from improving component-level inspection information without a means for exploiting that improvement at the facility or installation level.

Currently, component-level inspection information is not considered useful or of prime importance at many installations. This situation is demonstrated by the high percentage of installations that are not doing component inspections on a regular basis. Of the 109 installations surveyed or interviewed for the study, 60 have a scheduled inspection program in place (55 percent). Eighteen installations are doing no inspections. In other cases, inspections are done, but the information is not used. One ERM manager interviewed indicated the inspection results "sat on the shelf" because they were not in a form that was helpful in making management decisions. DEH managers at several key installations nationwide indicated that when detailed component inspection information is gathered, the results cannot be compiled in a format that enables it to be incorporated into the maintenance decision process. As a result, the information remains unused. When the information is not used, the logical next step is simply to stop doing inspections, which is exactly what many installations have felt compelled to do as a means of using scarce resources most efficiently.

Interview and survey results indicate that, almost universally, installations see the need for more inspection information and better tools with which to make maintenance decisions. Providing such a capability requires technology that combines the collection of physical data about facility components with the incorporation of that data into decisions on maintenance practice.

The ultimate goal of component inspection is to generate information to make optimal decisions about M&R. From this broader perspective, inspection technologies involve not only sensors capturing data from in-situ components, but also the systems that can transform this physical data into useful information to support management decisions. Such systems use data base management and information processing concepts.

A wide range of data base management technologies is available today. Information processing capabilities have expanded to include simulation, optimization, and knowledge-based analysis and interpretation. Software for implementing these data base and information processing capabilities is available for any size computer hardware. The software's level of complexity is not necessarily dependent on computer size. The combination of sensor hardware and data base with information processing software offers a wealth of technological options with great potential to aid in maintenance decisions. However, selection and application of the appropriate technology demands an understanding of how the maintenance information requirement is structured. The relationship between technology and information requirements is discussed in the next section.

Information Requirements and Technological Potentials

A general model of how information requirements are structured for an Army installation will help illustrate which technologies would be appropriate at different levels in the maintenance management

process. Three distinct levels of information are required to support this process (Figure 6).[12] Level 1, the installation level, deals with maintenance budget decisions, priorities, project justification, and manpower programming, and needs to be supported by usable information generated from an accurate assessment of each facility on the installation. Level 2, the facility level, must be able to provide information "up the line" to support management needs in Level 1. It must also be able to generate and store information for the component level, supporting the detailed inspections and results done in Level 3. Level 3, the component level, must provide the precise condition data for individual components within a facility.

Table 1 relates management decisions and information requirements of those three levels to technology options. It is structured to show how management decisions, the information required to support these decisions, and the appropriate technologies to capture the needed information vary, depending on the decision level. The approach to capturing, handling, and using the necessary information also varies with the decision level. The column under "decision types" indicates the kinds of decisions made at each of the three levels. The "information requirements" column indicates the type of information and data needed to support these decisions. The "approach" column suggests generic approaches to providing the needed information and data, and the "technology" column indicates specific technologies that could support the implementation of these approaches. The suggested technologies are based on the authors' experiences. The purpose of the table is to provide a broad perspective from which specific recommendations will be made. A more detailed description of the terms used and relationships suggested in Table 1 is presented in Appendix C.

The discussion of Table 1 below identifies information requirements and potential technologies for providing this information. The discussion of technology is broad. The focus, however, is ultimately on technology for collecting data that describe physical conditions of facilities and components. The following paragraphs summarize the needs raised in the table and identify areas where technology could be developed to meet these needs.

Each of the three decision levels discussed above has distinct information needs that could be satisfied by new or existing technology.[13] At the installation level (Level 1), an integrated data base and data base management system would support DEH management with accessible information covering the full inventory of facilities. Such a system could potentially provide integration of numerical, geographical, line drawing, and field data components, which would be used in combination to support maintenance decisions. Considerable field data would be required for a complete inventory assessment. This requirement could be met using available imaging technologies (visual, infrared) developed in remote sensing. The remotely sensed image data could be reduced rapidly and entered into the data base using commercially available image-processing and data entry technology. The data base described above could support resource allocation models that optimize installation performance within available resources. Expert systems, which automate the analysis of tradeoffs and paybacks, could have significant potential in implementing resource allocation models.

The facility level (Level 2) deals with detailed information on facility inventory and condition. Field data collection needs at this level are extensive, and could be met using high-speed remote sensing systems and other sensory devices. Commercial data base management software used for facility management applications is available at this level. The data bases used in this software could be broadened to integrate geographical, line drawing, and field data components. This broadening would enhance the support of information needs at this level, and would enable more interactive and wider use of the data base. The information in such a data base could be used to support the

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[12] K. R. Maser, "Sensors for Infrastructure Assessment," *ASCE Journal of Performance on Constructed Facilities*, Vol 2, No. 4 (November 1988) pp 226-241.
[13] K. R. Maser.

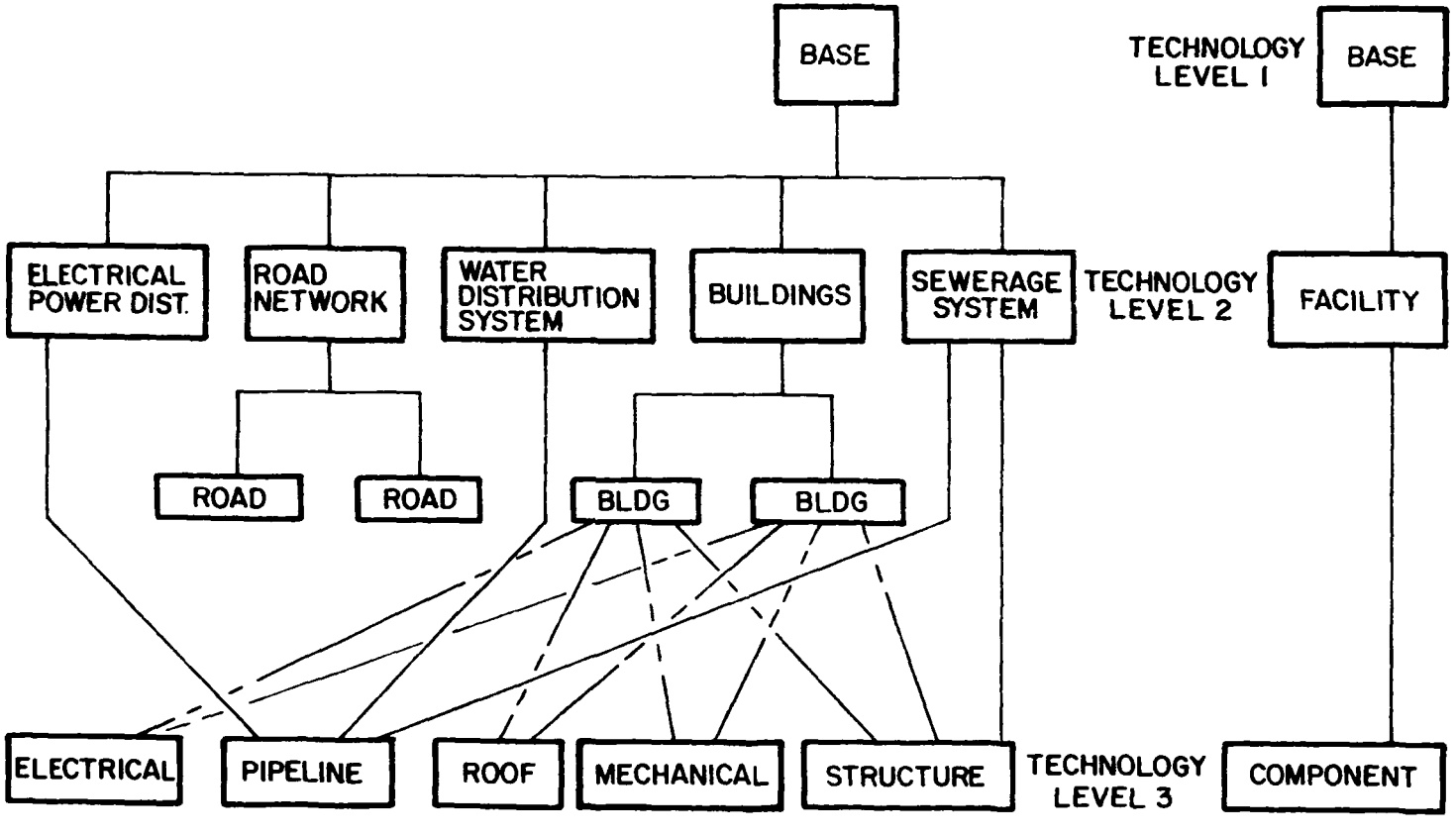

Figure 7. Information levels.

Table 1

Information Technology for Maintenance Decisions

Decision Level	Installation	Facility (and Facility Type)	Component
Decision Type	Inspection programming and resource allocation Maintenance decisions Maintenance budget	Inspection methodology (individual and collective) Maintenance specifications Repair/replace/no action	Frequency, extent, and technology of inspection Repair/replace/ no action
Information Requirements	Inventory data Performance data and impact of maintenance on facility performance Impact of facility performance on function of installation Cost of maintenance	Inventory and inspection of facilities (condition and performance) Condition/performance assessment Impact of maintenance on past and future performance Cost of maintenance Maintenance needs	Physical characteristics Condition and performance rating Diagnosis of condition cause Projection of future life and performance Cost of maintenance Maintenance needs
Approach	Automation to aid in data acquisition Data base management Resource allocation Optimize life-cycle cost	Automation to aid in data acquisition Data access and data base management Automated data transfer (from hard-copy records) Programmed inspections Decision models and life-cycle analysis	Automation to aid in inspection, condition sensing, and and data interpretation Life-cycle cost analysis

Table 1 (Cont'd)

Technology	Remote sensing (inventory), automated image processing, and automated data entry	Remote sensing of inventory and condition	Machine vision
		CAD	Nondestructive evaluation methods
	Data base management systems (DBMS) and geographic information systems	DBMS	Geophysical techniques
		Electronic clipboard	Expert systems
	Expert systems	Optical scanners and bar codes	CAD
			Voice systems
		Inventory sensing devices	
		Expert systems	
		Voice systems	

O&M personnel as well as overall management needs. This data base also could support models that predict a facility's performance based on the condition of its components and other supporting data. Such models would provide a basis for facility maintenance decisions. Other models could be developed to relate the impact of component inspections and maintenance to component condition and facility performance. The output would serve as a basis for programming inspections.

Component level (Level 3) technology is needed to provide accurate, comprehensive condition data for individual components within a facility. Technology at this level is component-specific, with the objective of measuring or monitoring a specific physical feature of interest within a component (e.g., presence of moisture, thickness of pipe tubing, amount of vibration). Data representing these physical features must then be interpreted and the component condition assessed. Computer software plays a key role in these areas, both in processing sensor data and enabling the data to be entered into the system automatically. At present, the Army's ability to collect specific data about the condition of a component exceeds its ability to use the data in a useful manner. The need, therefore, is to expedite the entry of detailed component-level data into the facilities management system and to automate its interpretation. Since the traditional and most prevalent method of component inspection is visual, automating visual data collection and interpretation ("machine vision") would provide a means of efficient data capture and entry. Expert systems for interpreting and evaluating component condition based on field performance data would also contribute to this level of activity.

The above discussion is a broad statement of the Army's maintenance information needs and the technological potential for meeting these needs. Generally, the higher the decision level, the less detail is needed to support the decision process. Also, the information needs at the various levels can often be satisfied by information collected at a lower level via the appropriate technology. Detailed component information can, in many instances, be "rolled up" at the facility level and the installation level. Before recommendations can be generated, it is important to recognize current technological developments within the Army aimed at meeting some of these needs. The next sections summarize two efforts in this area.

The Integrated Facilities System (IFS)

The Integrated Facilities System - Mini/Micro (IFS-M), under final testing at USAEHSC, implements the concepts described in the previous section. The first generation system (IFS-I) was an automated management information system that encompasses the life-cycle management of the Army's real property. It was intended to provide information on all aspects of facilities engineering activities as well as to offer a single-source data base of physical and budgetary information. IFS-I was designed to provide upward reporting of resources as well as support for DEH operations at all installation levels. It operated in a mainframe computer "card in/paper out" batch environment. Technological advances in mini- and microcomputers, as well as changing information requirements at the installation level, have resulted in the need to redesign the system. In March 1986, the Office of the Chief of Engineers (OCE) decided to build a new tool for the DEHs which would operate in a mini/micro-computer network environment to comply with the Army standard systems architecture. The result of this decision is the current IFS-M development effort.

IFS-M can be considered as the "Army Management System" with regards to facilities management and presents the opportunity to implement the concepts described in the previous section. Through a single system operated on a single computer, IFS-M will be a tool to help manage the DEH operation much like IFS-I was intended. However, through extensive software development and the use of local minicomputers, IFS-M should provide users with a system that can be easily adopted and used. As such, it should support decision-making at all three decision levels. IFS-M was designed around a data model that is independent of organizational structure and existing automated systems. Once a particular data model was developed, it was implemented to the field incrementally so as to maximize utility of the ultimate system. This process was accomplished through packaging and prioritizing pieces of the data and activity models. These pieces were referred to as "Prototype Development Method (PDM)" projects. The following PDM projects were the first six to be identified for the new system:[14]

1. Real Property: this module maintains the inventory of the installation's real property. It also supports the branch of the DEH that is responsible for making facility assignments and maintaining records of facility use.

2. Customer Service: this module tracks the movement of a customer request from initiation through completion, ensuring that as one branch of the DEH fulfills its responsibility, the next branch is ready to begin.

3. Job Cost Accounting: this module provides the capability to monitor obligations and expenses by job, reimbursable order, specific funding program, special DEH interest, and facility, and for technical data reporting.

4. Contract Administration: this module provides the ability to monitor contracting activity from time of award until financial completion, to monitor payment requests and payments, and to report on contract payments and status.

5. Work Estimating: this module supports conceptual and detailed cost estimates of potential or designated work projects.

6. Supply Interface: this module interfaces with other Army computerized supply systems so DEH managers know which materials are available from Army supply sources for planned projects.

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[14] *Functional Description Prototype Development Methodology, Integrated Facilities System, Mini/Micro (IFS-M).*

Future functional enhancements to IFS-M will provide the DEH with information in the following functional areas: (1) project planning and mission coordination, (2) employee data, and (3) plan, program and track requirements.

These completed and future PDM projects have been or will be developed into modules on an integrated software package supporting the full range of DEH operations. The hardware specified for IFS-M at the DEH departmental level is the Unisys 5000-80 minicomputer with terminals and the capability of being linked to IBM-compatible microcomputers. The microcomputers supplied with the Unisys system are Zeniths. The Unisys 5000-80 has a storage capacity of 1 to 2 Gb which is expandable upwards. The Unisys are 32-bit machines with 16 Mb random access memory (RAM). The Zenith micros have a 20-Mb hard disk (expandable to 40 Mb) with 640 Kb of RAM. The Zeniths use an 80286 Intel board for the main processor and have an Intel 80287 math coprocessor. A Unisys microcomputer is also expected to be available for the system, which would have bar coding capability.

At present, IFS-M is envisioned primarily as an operational support tool. Development of its full potential in maintenance management would require some type of integration with the EMS family (discussed in the next section). An interface between IFS-M and EMS is under development with the goal of treating EMS in a similar fashion as the PDM projects. Each EMS would maintain its own detailed data base, but when the interface is completed, each EMS would be able to exchange certain information with IFS-M. It is intended that the IFS-M data base be much less detailed in inventory, inspection, condition, and performance information than the EMS data bases. In this context, level 1 data collection technology would interface directly with an expanded IFS-M, whereas levels 2 and 3 data collection technology would interface with the EMSs. The development of these interfaces is described in more detail in Chapter 6.

Engineered Management Systems (EMS)

An EMS is defined as the systematic use of engineering technology to determine when, where, and how to best maintain facilities or their components. Generally, these systems are microcomputer-based, but that is not a prerequisite to system use. Key to the EMS concept are the structured techniques, procedures, and processes necessary for effective maintenance management. Included in this concept is the need for facility or component inspection information. EMSs are not expert systems, but rather maintenance management decision-support tools. Generally, EMSs are intended to support decision-making at facility or component levels (levels 2 and 3 in Table 1).

The EMS Family

USACERL has been active in EMS development for several years. Currently, nine systems have been or are currently being developed which cover a large proportion, but not all, of the facilities found on a military installation. Other systems are possible. These systems are described briefly below:

1. PAVER.[15] This EMS is the first and most fully developed system. PAVER applies to all surfaced areas including airfields as well as roads and streets. It covers asphalt, jointed concrete, and unsurfaced pavements. PAVER has been implemented successfully at more than 200 military installations and civilian communities and airports.

[15] M. Y. Shahin and S. D. Kohn (October 1981); M. Y. Shahin and S. D. Kohn (March 1982).

2. RAILER.[16] The RAILER EMS has been developed for use on military as well as civilian short-line railroad networks. Having been field-tested, RAILER is available for commercial implementation with initial sites scheduled for FY89.

3. BRIDGER. Military highway, railroad, and pedestrian bridges are encompassed in this EMS. Still in the developmental stage, BRIDGER will be field-tested during FY90 and ready for commercial implementation in FY92.

4. PIPER.[17] Underground utility piping systems, specifically gas and water, are covered in the PIPER EMS. The system is currently being field-tested and demonstrated, and is expected to be ready for commercial implementation in FY90.

5. SCALER. This system is a component-specific EMS for corrosion mitigation and management of building interior potable water and condensate return lines. Field testing and demonstrations will be completed in FY89; commercial implementation will begin during FY90.

6. ROOFER. This [illegible] component-specific EMS--in this case, for M&R of built-up roofs. Field-testing and demonstrations will conclude in FY89, with commercial implementations planned for FY90.

7. PAINTER. Painted interior and exterior surfaces of buildings and structures are the subject of the PAINTER EMS. Still in the development stage, PAINTER will be field-tested and demonstrated in FY89. Projected implementation is FY90.

8. BUILDER.[18] This EMS, begun in FY88, is in the initial development phase and should prove to be the most complex and encompassing system. All military building components will be included to permit management at the facility level. Integration of ROOFER, SCALER, and PAINTER is being studied as part of the approach. An initial report outlining the proposed system will be published in the near future. BUILDER is expected to take a few years to complete.

9. Installation Engineered Management System. The system, begun in FY89, is intended to integrate the existing EMSs and any new systems developed. Advanced prediction and optimization techniques will be incorporated to obtain the maximum benefit from expended M&R funds. This particular EMS is specifically designed to accommodate installation level (level 1 in Table 1) decision support. This EMS will take several years to complete.

Why EMS?

The EMS concept was defined earlier as the use of technology to best maintain facilities. The rationale for this approach is illustrated in Figure 8, which shows a generalized pavement deterioration curve.[19] As time passes, quality (or condition) decreases and with that decrease is a substantial increase

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[16] D. R. Uzarski, D. E. Plotkin, and D. G. Brown, *The RAILER System for Maintenance Management of U.S. Army Railroad Networks: RAILER 1 Description and Use*, Technical Report M-88/18 (USACERL, 1988).

[17] A. Kumar, W. Riggs, and M. Blyth, *Demonstration of the Pipe Corrosion Management System (PIPER)*, Technical Report M-86/08/ADA166807 (USACERL, April 1986).

[18] D. R. Uzarski, E. D. Lawson, M. Y. Shahin, and D. E. Brotherson, *Development of the BUILDER Engineered Management System for Building Maintenance: Initial Decision and Concept Report*, Draft Technical Report (USACERL, 1989).

[19] C. Johnson, *Pavement (Maintenance) Management Systems* (American Public Works Association, 1983).

in M&R costs. Thus, if similar deterioration curves could be established for the desired facilities or components, facility managers could determine where they are located on the curve at any point in time and make the prudent decisions regarding when to do work. Also, depending on the course of action chosen at the time of M&R, the shape of the curve could be altered. This process ensures that scarce M&R funds are allocated most appropriately, producing a significant cost avoidance. The difficulty is that no single deterioration curve would apply to all facilities. In fact, at least for pavements, the deterioration curve differs between individual pavement sections.[20] The EMS's strive to establish those curves through engineering technology.

EMS Components

As shown in Figure 9, five major components form an EMS: inventory, condition survey, data base and engineering tools, network-level management, and project-level management. Each component is summarized below.

Inventory. This is one of the two EMS inputs. It is imperative that managers know "what" and "how much" to manage. This input may include items such as the amount in square yards of airfield runway or the total length of underground water pipes present at the installation.

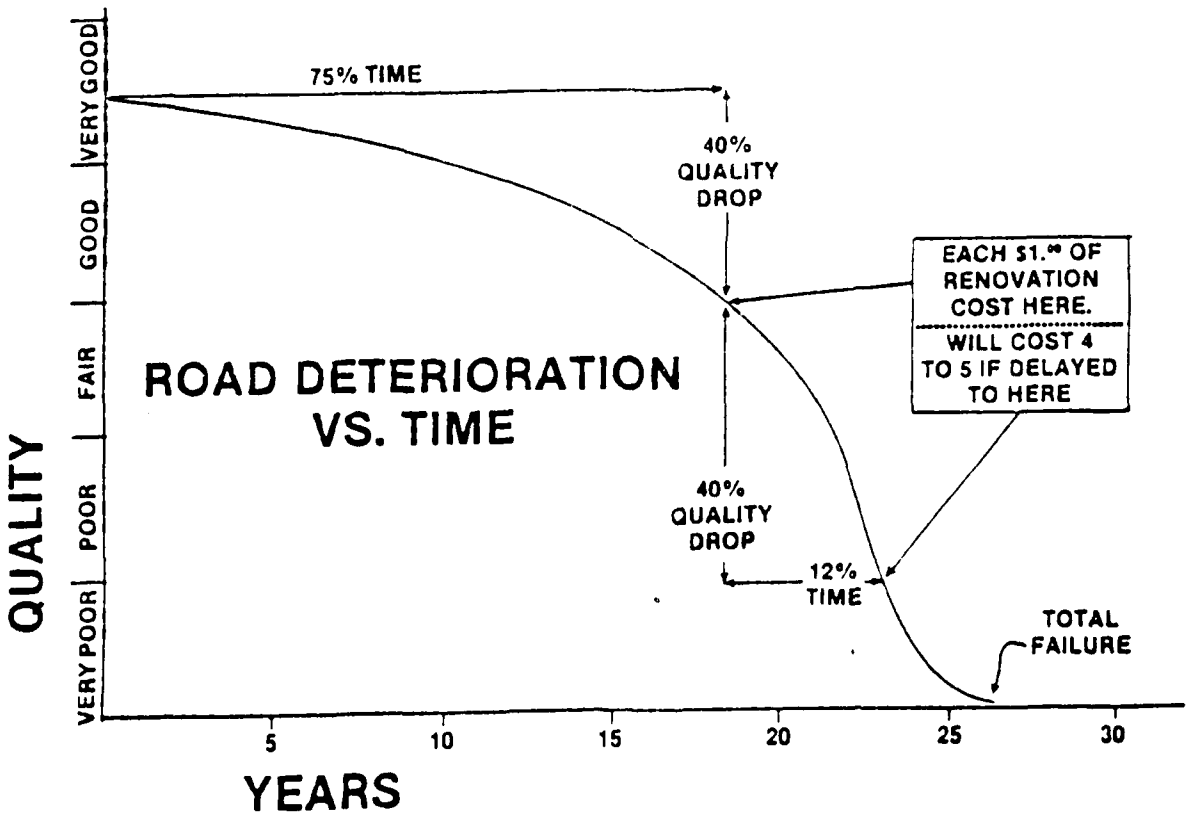

Figure 8. Generalized pavement deterioration curve and estimated costs associated with each level of deterioration.

[20] C. Johnson.

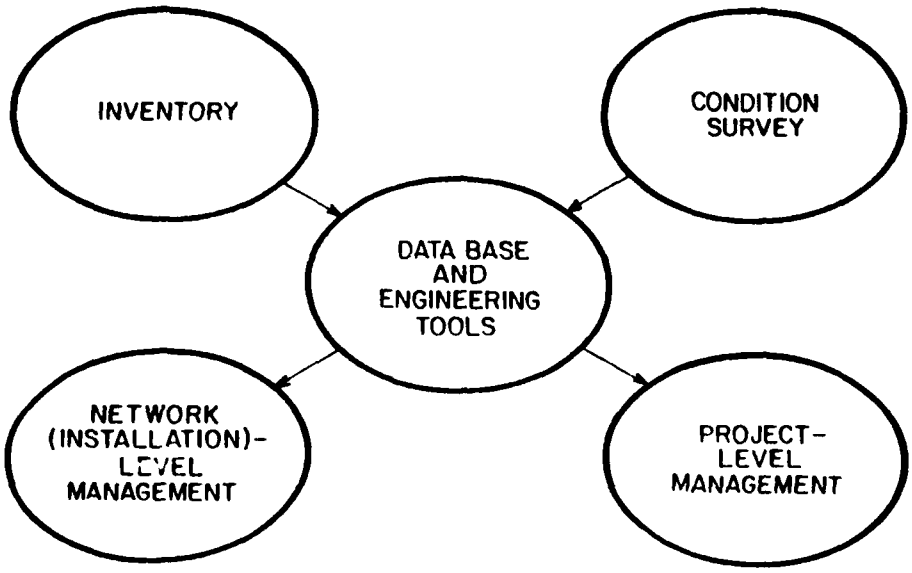

Figure 9. EMS components.

In addition, "management units" must be defined as part of the inventory. Each facility or component to be managed requires division into and identification of relatively uniform physical units. This uniformity considers use, age, materials, etc., and forms the physical basis on which to apply the entire maintenance management process. Because of the relative uniformity, each management unit will have a somewhat unique deterioration curve and perhaps different M&R needs. Since each is a single entity, inventory, inspection, and other data such as work history will be collected for it. M&R strategies can be developed specifically for each unit so that when work is done, it will be applied to the whole management unit (or groups of units). For example, a single street may consist of several pavement sections (management units). Similarly, a building may have several unique roof sections.

Inventory data collection is a "one-time" procedure that requires updating only if the physical characteristics or materials change through M&R. The specific inventory and historical needs are a function of the individual EMS.

Periodic Condition Survey. This component is the other basic EMS input. Managers require a periodic condition survey so that they can ascertain the "health" of the facility or component. This information allows managers to determine where on the deterioration curve (Figure 8) the facility or component is at that point in time and as a point of departure for predicting future condition. At present, this survey predominantly relies on visual assessment, but nondestructive testing (NDT) and laboratory tests are also employed if needed and practical. It is envisioned that, ultimately, the entire facility and component inspection process will be accomplished in direct support of EMS which, in turn, will directly support IFS-M.

EMS Data Base and Engineering Tools. The inventory and inspection data that are collected for each management unit comprise the EMS data base. Each EMS has its own data base and, generally, only one data base will be created for each installation. However, depending on the EMS, it is possible to have multiple data bases for a given installation. For example, within PAVER, one data base may be created for all surfaced areas, but different data bases may be created for airfield or road and street pavements at a single installation.

USACERL and USAEHSC have expended considerable effort in ensuring compatibility between IFS-M and EMSs. Each system has its own data base, but the EMS data bases are much more detailed than the IFS-M data base for a given facility. Due to the need for and use of each system, this approach is to be expected. However, certain data elements should be the same in an EMS and IFS-M. Therefore, procedures are being developed to transfer appropriate information between systems. This capability will ensure consistency in the information and avoid duplication of effort in collecting and loading/updating data. Since the EMS data bases are being created based on the management unit and IFS-M is based on the facility, some EMS data will need to be combined, as appropriate, for transfer. Also, certain data being downloaded from IFS-M to an applicable EMS will have to be apportioned to affected management units.

The engineering tools developed for EMSs use the inventory, inspection, and other appropriate data to perform decision-support analyses. Common to all systems is a condition evaluation and rating procedure, condition prediction, M&R guidelines, and life-cycle cost analyses. Individual EMSs also use appropriate engineering technology specific to facility type or component in order to perform other decision-support tasks.

The condition evaluation and rating procedure involves a condition index. Each system uses an identical rating scale as shown in Figure 10. The condition index represents a key system element as it is the measure of health for a specific management unit or the entire group (or subgroup) of management units. It is through the use of the index that the deterioration curve (Figure 7) is established. Once established, condition predictions can be made which allow managers to schedule M&R. The condition index can also be used to correlate M&R strategies, as Figure 11 shows.

The first condition index developed was the Pavement Condition Index (PCI).[21] This index and the Corrosion Status Index (CSI) for underground gas pipes[22] are single-component indexes. The same will be true for other piping indexes being developed. The recently completed Roof Condition Index (RCI)[23] is a composite of three condition indexes--membrane, flashing, and insulation. This same approach is being taken in development of the Track Structure Condition Index (TSCI), Building Condition Index (BCI), Bridge Condition Index (BRCI), and Coating Condition Index (CCI) for paint.

Another engineering tool that each EMS will have is an engineering economics module. This component will permit the user to perform life-cycle cost analyses of various M&R alternatives and strategies. Also, some of the EMSs will incorporate mathematical optimization models and other technology-based features germane to the specific system.

Network-Level Management. Network-level management is an EMS output that focuses on the entire group of management units associated with the specific EMS. This level of management generally encompasses the facility-level (level 2) decisions depicted in Figure 6 and Table 1. Included, for example, would be all of the pavements, railroad track, or built-up roofs, respectively, at a given installation. This level tends to focus on the "where" and "when" aspects of facility management. Network-level management should be performed annually.

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[21] M. Y. Shahin and S. D. Kohn, *Development of a Pavement Condition Rating Procedure for Roads, Streets, and Parking Lots, Vol I: Condition Rating Procedure*, Technical Report M-268/ADA074170 (USACERL, July 1979).

[22] A. Kumar, E. Meronyk, and E. Segan, *Development of Concepts for Corrosion Assessment and Evaluation of Underground Pipelines*, Technical Report M-337/ADA140633 (USACERL, April 1984).

[23] M. Y. Shahin, D. M. Bailey, and D. E. Brotherson, *Membrane and Flashing Condition Indexes for Built-Up Roofs, Vol I: Development of the Procedure*, Technical Report M-87/13/ADA190368 (USACERL, September 1987).

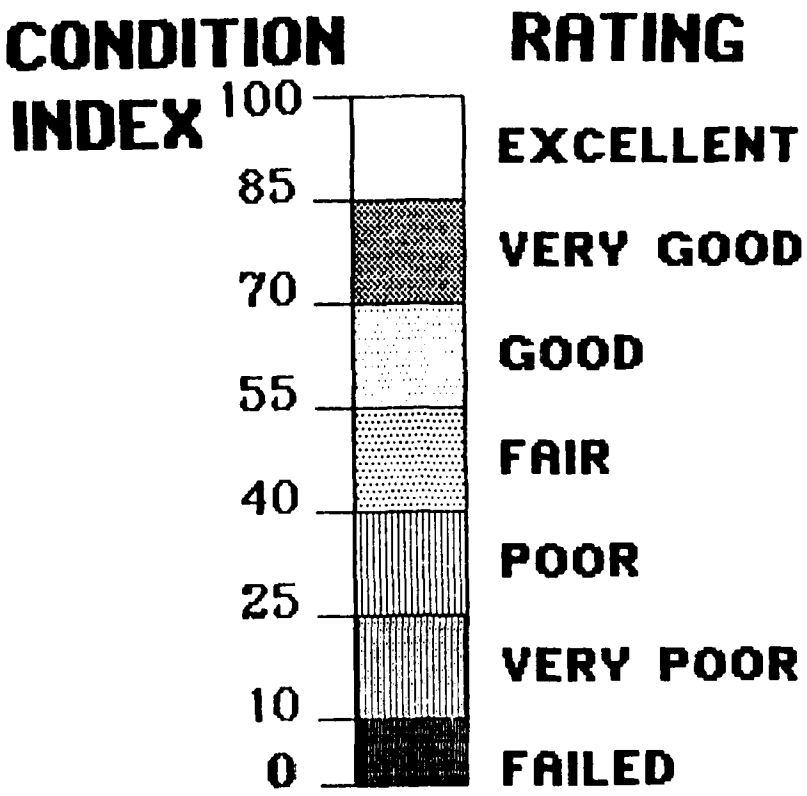

Figure 10. Condition Index rating scale.

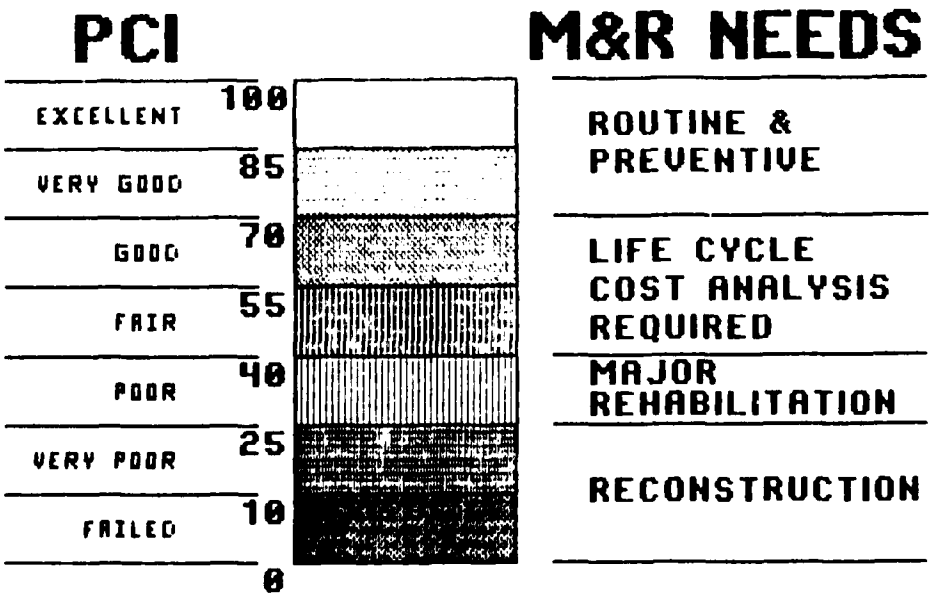

Figure 11. Pavement Condition Index (PCI) vs. M&R needs.

The condition index also plays a key role at this level. As discussed earlier, current and future condition can be assessed. This assessment, in turn, leads to the identification of candidate management units for M&R which then must be prioritized for actual work completion to meet budgetary constraints. Short- and long-range work plans result. Budgets can be optimized at this level through the best use of available or planned dollars.

Network-level management through EMS permits the manager to do "what-if" analyses. For example, the costs (budgets) associated with establishing a minimum acceptable condition index at various target levels can be projected. Also, the effects of deferred maintenance or budget cuts, in terms of index value reduction, can be determined.

As described earlier, inspection information is needed in order to make this approach feasible. Fortunately, at the network level, the inspections need not be greatly detailed nor extensive. Using PAVER as an example, network-level inspections needed for the periodic condition surveys are performed only every 2 to 3 years (average) on a given pavement section and, when inspected, only approximately 10 to 15 percent of the pavement area within the section is actually surveyed. The inspections are visual and a 2500 sq ft area can be inspected in about 10 to 15 min.

Project-Level Management. Project level management is performed only on those management units, such as specific roofs, scheduled for M&R during the next annual work plan. Project-level management generally encompasses the facility- and component-level (levels 2 and 3) decisions described in Figure 6 and Table 1. The information as to which management units those will be is input from the network-level management phase. The level of effort associated with this level depends on the work to be performed. This level focuses on the "how best" to maintain the facilities.

If the work to be done is very routine or preventive in nature, a service order or work request (discussed in Chapter 2) would be issued. The work would then be planned, estimated, and scheduled through normal job order or contracting procedures. The need for an EMS is limited to inventory retrieval and/or extrapolated distress quantities. Additional inspection is normally not required.

If the work to complete consists of repairs, major M&R, or rehabilitation, additional facility management actions are required. Since severe deterioration, local failure, or complete management failure has occurred, it is critical that the cause of the failure or deterioration be diagnosed so that feasible M&R alternatives can be identified that will rectify the cause of the problem and not just treat the symptoms. The goal is to prevent a recurrence of the problem after repairs are finished. Ultimately, as part of EMS, the best alternative should be selected considering life-cycle costs and other tangible and intangible factors. This process permits optimization of funds at the project level.

As part of the diagnosis process, additional information usually is needed, including further visual inspection and NDT and laboratory testing, if applicable. Recall that the network-level inspection process was done mainly to determine the health of the management unit and the network as a whole. At the project level, just knowing that the management unit is "unhealthy" is not enough. Additional information is now required in order to perform the proper diagnosis for determining why the unit is unhealthy and what remedies are possible. The visual effort will generally consist of a 100 percent inspection. NDT and laboratory tests may be needed when the visual techniques are inappropriate or incomplete for the analysis. This inspection and testing may be performed by contract or by personnel from the Engineering Plans and Services (EP&S) Branch or the Estimating and Facility Inspection Branch (see Figures 1 and 2).

Once the most feasible alternative is selected, the design is finalized and costs are estimated. A job order would be prepared for in-house work or plans and specifications prepared as part of a contract package. The final step in the project-level management process is to update the data base to reflect the work completed.

The weak link to EMS system acceptance and use is the inspection process needed for the period condition surveys. For most systems, the inspection process is labor-intensive and time-consuming. Depending on the systems, this drawback has led to dependence on sampling techniques and/or different levels of inspection detail. Without good and relatively current condition information, it is very difficult to properly manage facility maintenance in a proactive sense. The use of technology to improve the condition assessment process is addressed in the next chapter.

4 ASSESSMENT OF TECHNOLOGICAL OPPORTUNITIES

Overview

The discussion in the previous chapters suggests that the flow of inspection information into a useful maintenance management framework is a weak link in the Army's overall facility management program. The limited availability of inventory data and the effort required to collect and update it are identified as other problem areas, considering the importance of this data. Consequently, improvement of inspection technology alone can only address part of the problem. Part of the "information flow" issue is the methods by which inspection and inventory data are collected. For example, visual inspection, which is the most prevalent type of component inspection, involves manual recording of data and manual transfer of those data to a management data base. Clearly, a technology that could automate the way this data is acquired and transferred would do much toward enhancing the flow of information. The same would be true for other types of inspections, and for inventory data as well. This chapter presents some areas of technological opportunity in further detail.

Numerous technologies have evolved in recent years that have potential for automated collection, evaluation, and transfer of component inventory and inspection data. These tools have been developed using a combination of computer software and sensor hardware. The key elements of these tools are:[24]

1. Sensor hardware: physical devices that receive some external signal (optical, thermal, etc.) and convert it into an analog or digital voltage. Recent developments in sensor miniaturization and attached microprocessors have revolutionized the power and versatility of sensing devices. These tools are used primarily at the component level, providing detailed information about the physical condition of the component being evaluated. This is the physical information that becomes the basis for component-level maintenance decisions. Infrared scanning of built-up roofs or electrical systems is an example of a sensor hardware application.

2. Recording hardware: includes analog and digital magnetic tape recorders, and floppy and hard disk drives used in the field to retain raw and preprocessed signals generated by the sensors. Developments in conventional electronics have improved analog recording techniques, and microcomputers have brought powerful digital recording capabilities to field applications. Video cassette tapes of infrared scanning data are an example of output from this type of hardware. This output is unprocessed component condition data.

3. Data collection methodology: this relates to the way in which the sensors are deployed to collect data. The method depends on the type and number of components being investigated. Infrared thermography with a hand-held sensor can be used on a single built-up roof, or, on a number of roofs, the sensor can be mounted on an aircraft for detection from the air.

4. Computer interface: devices and software that collect the signals from the recording devices, convert them into digital format, and make them accessible for further processing. The microcomputer revolution has impacted this area with countless analog/digital conversion devices, frame grabbers, bar-code readers, and other direct data entry techniques. It is at this point that the component-level data are translated into a format that can be processed by the computer.

5. Signal and data processing: techniques used to obtain the relevant data base items from raw sensory input data. Microcomputers again have made powerful processing algorithms available in low-cost commercial packages. Knowledge-based techniques and expert system "shells" provide additional

[24] K. R. Maser (November 1988).

means of automating data processing. This is the point at which the physical condition information about a component is integrated into the larger facilities data base. Using software, the information can be analyzed to evaluate the condition of the individual component and determine appropriate maintenance strategies. It can also be aggregated and used in relation to other component and facility data to provide information on the condition of a facility as a whole.

These tools are being integrated into high-speed sensor systems to serve facility and infrastructure inventory and condition information needs. USACERL has assessed specific developments in these areas for their potential application to Army facilities management, as discussed below.

Component Inspection and Condition Evaluation

A great deal of activity is occurring in the development and application of component condition measurement methods and devices. Various reports summarizing these activities and the measurement capabilities that currently exist can be found in the literature. Technical Report REMR-CS-1,[25] for example, discusses technology and methodology for inspection of concrete components. Another example is USACERL Technical Report M-305,[26] which presents a comprehensive review of nondestructive evaluation (NDE) methods used for the inspection of building materials. (Appendix D of this report presents a synopsis of 29 different methods originally included in M-305.) A recent infrastructure study by the National Research Council[27] summarized the various NDE technologies and their capabilities for component inspections. This summary is presented in Table 2 and reveals a wide variety of technologies and measurement capabilities.

At this point, it would be tempting to summarize the material in the above references with specific emphasis on Army facilities management. It is clear from the discussions in Chapters 2 and 3, however, that the issues raised in the present study go beyond assessing the capabilities of specific technologies to inspect specific components. It has been shown, for example, that component inspection information often goes unused due to its lack of integration with an overall management scheme. Consequently, this chapter focuses on examples of technology with inherent potential for collecting large quantities of relevant information and for efficiently transferring that information into a management system. The first example is a method that relies on human visual inspection, but eliminates the need for manual recording and data transfer. Following that are examples of automation that eliminate the reliance on human visual techniques.

Voice-Operated Inspection System

The Voice-Operated Inspection System (VOIS®) allows an inspector to verbally log visually observed inspection items into a hand-held tape recorder. The tape is later played into the VOIS® and an inspection report is generated automatically. The system, initially developed by USACERL and completed under a Cooperative Research and Development Agreement (CRDA), consists of a personal computer, printer, tape deck, and voice recognition board. The VOIS® is currently being tested through the American Public Works Association (APWA) for construction inspection, building code inspection, and pavement inspection for PAVER. Some of the advantages of this system include the

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[25] R. L. Stowe and H. T. Thornton, *Engineering Condition Survey of Concrete in Service*, Technical Report REMR-CS-1 (U.S. Army Waterways Experiment Station, September 1984).

[26] J. Clifton, N. Carino, and P. Howdyshell, *In-Place Nondestructive Evaluation Methods for Quality Assurance of Building Materials*, Technical Report M-305/ADA112869 (USACERL, March 1982).

[27] National Research Council, Committee on Infrastructure Innovation, *Infrastructure for the 21st Century - Framework for a Research Agenda* (National Academy Press, Washington, DC, 1987).

Table 2

Features Measured by Various NDE Methods

Features	Voids & Cracks	Strain	Density	Motion	Location of Reinforcement & Interface	Corrosion	Moisture	Dimensional Stability & Warpage	Location of Embedded Structures	Leaks
Radiography	G	F	G	N	G	F	N	N	G	N
Neutron scattering & reflection	N	N	G	N	N	N	G	N	N	N
Visual	G (surface)	N	N	G	N	G	G	G	N	G
Television	G (surface)	N	N	G	N	N	N	N	N	G
Photography (stero)	G	F	N	N	N	G (outside)	N	G	N	N
Holography	F	G	N	G	N	N	N	G	N	N
Fiber optic sensor	G	G	N	N	N	N	N	G	N	N
Thermography	F	N	N	N	N	N	G	N	F	G
Ultrasonic testing	G	F	F	N	G	F	N	N	G	N
Acoustic resonance (seismic)	G (in concrete)	N	F	N	F	N	N	N	N	G
Acoustic emission	F (dynamic)	N	N	N	N	N	N	N	N	G
Correlation water leak testing	N	N	N	N	N	N	N	N	N	G
Eddy current	G (surface)	N	N	N	N	N	N	N	G	N
Ground radar	G	N	N	N	G	N	N	N	G	F
Magnetic field measurements	F	N	N	N	F	N	N	N	F	N
Displacements (gauge)	F	G	N	G	N	N	N	G	N	N
Strain gauge	F	G	N	G	N	N	N	G	N	N
Dye penetrant	G (surface)	N	N	N	N	N	N	N	N	N
Odor sensor	N	N	N	N	N	N	F	N	N	G
Chemical	N	N	N	N	N	N	G	N	N	F
Leak detection	N	N	N	N	N	N	N	N	N	G
Electrochemical methods	N	N	N	N	N	G	F	N	N	N
Nuclear magnetic resonance	N	N	N	N	N	N	G	N	N	N

*Letters indicate relative detectability of feature by each technique: G = good; F = fair; N = not detectable.

elimination of manually recording information, a faster inspection, and more accurate reports that do not suffer from human memory loss of data.

Automated Component Inspection Technologies

Several technologies have been developed that eliminate the need for traditional human visual inspection or destructive field or laboratory testing. Table 3 shows three examples in the area of pavement inspection--one dealing with surface condition, one for roughness and profile, and another for subsurface condition. High-speed sensing technology has focused on pavements because they represent a component which is extensive, and for which data collection is difficult and time-consuming. The technologies being developed for pavement, however, have generic capabilities that can be applied to other components. For example, automated surface condition assessment technology for pavement is now under development based on automated imaging and image processing. In these technologies, the pavement is illuminated either artificially or with natural light, and an optical sensor (e.g., a camera) picks up the pavement image. The image is then processed to identify distresses such as crack types, raveling, and spalling. This processed data can be automatically entered into a management data base such as that connected with PAVER. Similar types of automated surface inspection technology could be applied to building elements, railroad track, and other components. This inspection data could be entered directly into EMSs such as RAILER, PAINTER, and ROOFER.

Automated pavement longitudinal and transverse profile measurement technologies are already developed and in use. These devices use high-speed laser or acoustic distance measurement technology. The data are acquired and analyzed automatically, and can be entered directly into a pavement management system such as PAVER. Since distortional measurements characterize deterioration in many types of components, these technologies could also be extended to building envelopes and critical structural members.

Pavement subsurface evaluation using ground-penetrating radar is a relatively new technology which is still being developed; however, it has advanced enough to be applied in some cases. Current applications focus on void detection under concrete pavements. Future developments are looking at continuous evaluation of pavement layer thickness and moisture properties. Because of its high speed, noncontact, penetrating capabilities, radar has considerable potential for inspection of many types of components. Standard applications of radar focus on detecting subsurface objects such as reinforcing steel and buried pipes. Because of its inherent ability to detect subsurface moisture, the future will probably see more radar applications in component inspection where deterioration is moisture-related.

Two applications for which radar is currently under development are for bridge deck inspection and leak detection in buried water lines. In bridge decks, deterioration is moisture-induced. In water pipes, leakage produces subsurface moisture anomalies. In both cases, detection of the unseen moisture leads directly to a measure of the component's condition.

Infrared thermography is another technology with high potential for rapid data capture and transfer. An infrared camera is essentially a noncontact device that measures surface temperature and emissivity anomalies. Such anomalies are often related to subsurface problems such as moisture in roofs, delamination in reinforced concrete, and leakage of pipes. Infrared thermography applied to roofs and bridge decks is now standard commercial practice.

This discussion has dealt primarily with civil/structural components. However, the surveys discussed in Chapter 2 also indicated interest in the inspection of HVAC and electrical components. Because these components are relatively small and distributed, they do not lend themselves as easily to high-speed inspection and data acquisition as the larger components. Nevertheless, since these areas are important, USACERL studied technologies that might be applicable to their inspection. Table 4 summarizes the findings. Of particular note in Table 4 is the wide range of applicability for infrared

Table 3

Examples of Automated Component Inspection Technologies

Application	Technology	Status
Pavement surface condition	Optical imaging and image processing	Under development by several organizations*
Bridge deck and parking lot deterioration	Radar, infrared thermography	Partially developed; continuing R&D; commercially applied**
Pavement subsurface evaluation	Radar	Developed for void detection; under development for substructure evaluation and inventory of as-built conditions***
Roof moisture surveys	Infrared thermography	Developed and in use+
Pavement roughness and profile	Laser profile meter; response	Developed and in use++
Leak detection in underground pipes	Infrared, radar, and terrain conductivity	Under development+++

* K. R. Maser and J. P. Schott, *Automated Visual Imaging for High-Speed Inspection of Large Structures*, Final report, Grant No. ISI-8560729 (National Science Foundation, 1986).

**K. R. Maser, "Detection of Progressive Deterioration in Bridge Decks Using Ground Penetration Radar," *Proceedings, Experimental Assessment of Performance of Bridges* (American Society of Civil Engineers, 1986); W. M. K. Roddis, *Concrete Bridge Deck Assessment Using Thermography and Radar*, S. M. Thesis, MIT Department of Civil Engineering (1987); D. G. Manning and F. B. Holt, *The Development of DART (Deck Assessment by Radar and Thermography)*, Technical Report ME-85-03 (Research & Development Branch, Ontario Ministry of Transportation and Communications, 1985).

***W. J. Steinway, J. D. Echard, and C. M. Luke, *Locating Voids Beneath Pavement Using Pulsed Electromagnetic Waves*, National Cooperative Highway Research Program (NCHRP) Report 237 (Transportation Research Board, National Research Council, 1981).

\+ W. Tobiasson and C. Korhonen "Roof Moisture Surveys - Yesterday, Today, and Tomorrow," *Second International Symposium on Roofing Technology*, Gaithersberg, MD (1985).

++ NCHRP, "Equipment for Obtaining Pavement Condition and Traffic Loading Data," *NCHRP Synthesis 126* (Transportation Research Board, National Academy of Sciences, 1986).

+++K. R. Maser, "Detection of Leaking Fluids in Storage Facilities and Pipelines," *Proceedings of the International Workshop on Nondestructive Evaluation for the Performance of Civil Structures*, University of Southern California, Los Angeles (February 1988).

Table 4

Inspection Technology for HVAC and Electrical Components

Representative Components	Inspection Information Needed	Possible Technology
HVAC systems		
Electrical controls	Are contactors heating up due to overloads?	Infrared Thermography:* Detects heat caused by bad connections
Fan coil units	Condition of bearings	Vibration Analysis:** Detects vibrations caused by worn bearings
Air-handling units	Freezing of cooling coils	Infrared Thermography:* Detects temperature of coils
Steam traps	Temperature differentials at the diaphragm	Infrared Thermography:* Temperature gradient detected at the diaphragm
Boilers	Type of corrosion	Eddy Current Testing:*** Measures tube wall thickness
		Ultrasonic Testing:*** Measures the wall thickness
	Presence of heat exfiltration through boiler walls	Infrared Thermography:* Senses thermal anomalies on boiler wall
Steam distribution lines	Presence of steam exfiltration	Infrared Thermography:* Senses thermal anomalies at grade level caused by steam exfiltration of underground pipes
Electrical systems		
Transformers	Presence of "tracking at insulators"	Infrared Thermography:* Senses heat created by tracking
Service panels, motor control sensors	Presence of bad connections	Infrared Thermography:* Detects heat created by poor electrical contacts

*H. Kaplan, (Ed.), *Thermosense VIII, an International Conference on Thermal Infrared Sensing for Diagnostics and Control, Proceedings of SPIE*, Vol 531 (September 1985).

**N. C. Baxter, "Utilization of Vibration Analysis to Troubleshoot Rotating Equipment Problems," paper presented at the International Maintenance Conference, Chicago (October 1986).

***J. R. Clifton, N. J. Carino, and P. Howdyshell, *In-Place Nondestructive Evaluation Methods for Quality Assurance of Building Material*, Technical Report M-305/ADA112869 (USACERL, 1982).

thermography. Since this is a noncontact imaging technique, it has the potential for reasonably high-speed data acquisition. If the infrared data interpretation is automated or keyed in by the inspector, then it could be transferred rapidly to an EMS without further encoding.

Facilities Inventory and Condition Data Collection

In Chapter 3, inventory data, including component condition, were identified as critical in supporting installation- and facility-level management decisions. However, these data are often inadequate, inaccessible, and outdated, and upgrades can consume considerable resources.

The importance of applying new technologies for facility inventory and condition data collection is evident in the field implementation of PAVER which was described earlier as an EMS designed to optimize the allocation of M&R funds for pavements.[28] Installations that have implemented the system have found it an effective tool for aiding in pavement inventory, condition assessment, and M&R strategies. A requirement of implementation, however, is an initial detailed inventory and inspection for assessment of the pavement condition. Once completed, this effort provides the basis on which the pavement network is organized and analyzed. However, currently this groundwork is labor-intensive and the cost of initial system setup is a major consideration in evaluating whether to implement the system.

Army senior management has overcome this issue in many cases by having the MACOM pay for implementation on its installations (as described earlier for FORSCOM and TRADOC). Regardless of who pays, however, in the long run the high cost of initial inventory and implementation remains an issue for many. Labor-intensive inspections required to maintain the system are also an issue, although in some instances, they, too, have been funded by the MACOMs. Although maintaining and updating the system are not nearly as extensive as the setup, even the inspections required for maintenance are considered too much extra workload for maintenance staffs at many installations; they have to do it with in-house personnel. This work can be done by contractors, but it can be costly. Clearly, developing a tool that would reduce the labor and cost of both the initial data collection and followup inspections would promote more widespread use of PAVER and, as a result, improve maintenance of road networks and, in some cases, defer or negate the need for major M&R. The cost of a single major M&R project can pay for an entire implementation. USACERL is currently working on an automated pavement condition assessment tool to improve this situation. In addition, Micro PAVER, a microcomputer version of mainframe PAVER, has been developed to enable the system to be monitored and updated at the installation level, negating the need to use mainframe PAVER for that purpose.

The initial data collection challenge is an issue for other maintenance management systems as well. Interview and survey results from this study indicate that a number of installations have attempted to implement automated maintenance management systems on a variety of applications (HVAC systems, mechanical shops, structural components, and all facilities and components on an installation). In each case studied, the initial data collection was a critical issue. In several cases, the inventory and inspection problem effectively ruled out the use of an automated maintenance management system. Surveys and interviews with installation-level maintenance staff also established that a reliable and sufficiently detailed inventory and condition assessment of the facilities is not often available in a useful form. In some cases, it is only available in a foreman's notebook. As discussed in Chapter 3, accurate information of the facilities and components to be maintained is a fundamental requirement of an effective maintenance management program.

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[28]M. Y. Shahin and S. D. Kohn (October 1981).

It is also critical that this inventory be identified in units that are relevant and accessible to maintenance personnel. Typically, the existing inventory of facilities, components, and equipment is maintained in a format designed to meet financial and accounting criteria rather than the needs of maintenance managers and operations staff. Real property inventory is compiled in terms of broad facility type, usage, size, and materials. Maintenance personnel also need facility information in terms of components and systems within facilities, their physical condition, and performance. Maintenance requirements, the impacts of maintenance effort on performance, and the actual maintenance effort being given to specific components and subsystems are also needed.

There is a range of technologies in use and under development that would reduce the time and expense of gathering and updating the facilities inventory and condition data. Table 5 lists some examples. One application includes an "electronic clipboard" using bar codes, an optical scanner and portable computer, and ultrasonic measurement devices. This equipment allows large amounts of facility inventory and condition information to be captured and input in a short period of time. It also stores the data in a way that can be used effectively quickly after field collection without manual data transfer. Commercial facilities management consultants are using these tools now. The Daverman Company, for example, equips facility technicians with a hand-held HP 5000 microcomputer, a clipboard with optical bar codes representing different pieces of equipment, an optical bar code scanner attached to the computer and an Exergen ultrasonic distance measurement device. With this technology, the technician can collect information about facility space size, equipment, and condition, and file it in the computer. At the end of the day, the information is downloaded into the data base management system. Technicians using this system have been able to survey a maximum of about 150,000 sq ft of facility per day, although 35,000 sq ft/day is typical. A survey of this type was done successfully at Fort Irwin, CA. USACERL is currently researching the use of bar code technology for quality assurance inspections. Additional technologies with potential application include optical video laser disk, photologging, and computer image processing of video data. Several state transportation departments are using photologging on optical disk for inventory and condition data collection and management. These systems are described in more detail in Chapter 5.

Summary

Technology for rapid, efficient collection of inventory and condition data, and for automated transfer of those data to an EMS-type management data base offers the greatest potential for improved management of Army facilities maintenance. On the inventory side, optical imaging and image processing (also called "machine vision") offer significant potential to automate the arduous process of collecting and updating inventory data. The technology to automate the identifying, counting, and measuring of components is already developed and being used in several applications. On the condition side, it is clear that there is a wide range of components to be inspected for a variety of different conditions. From a technological viewpoint, however, infrared thermography and optical/video imaging stand out as having the greatest generic potential for addressing component inspection needs. Video imaging is a natural technological development, since it seeks to automate the most common form of component inspection (i.e., visual). Infrared thermography, with its "visual like" display, has developed rapidly over the past 10 years and has a generic ability to address a variety of inspection needs.

Based on the assessment of technologies in this chapter, it is concluded that the combination of optical and infrared imaging and image processing, applied to inventory assessment and component inspection, offers a future benefit for military facilities management unmatched by any other technology. These technologies involve similar data acquisition equipment (cameras), recording equipment (video cassette recorders) and data collection methodology. Consequently, they can be considered together under the heading "automated imaging technology." It is recommended that efforts be directed toward evaluating the variety of application modes that can evolve within this automated imaging concept. As a first step in this process, the next chapter describes the technology in greater detail and develops three application modes for both inventory and inspection.

Table 5

Examples of Automated Inventory and Inspection Technology

Application	Technolgy	Status
Building characterization	Video imaging	Under development*
Highway Photologging	Laser disk	Under development**
Pipe location	Radar	Under development***
Inspection data logging	Electronic clipboard (using optical bar coding)	Developed and in use (discussed in text)

* D. L. Schodek, U. P Gauchat, and R. Luft, *Patterns of Housing Type and Density: A Basis for Analyzing Earthquake Resistance*, Final Report, NSF Grant No. PFR-780-258 (National Science Foundation, 1984).

** *Better Roads, Laser Videodiscs, Computer Graphics for Road Evaluations* (March 1985).

*** GRI, *Development of Improved Construction and Maintenance Equipment and Techniques for Accidental Damage Prevention*, RFP No. 86-271-0229 (1985).

5 AUTOMATED IMAGING TECHNOLOGY

Background and State of the Art

The wealth of published literature and commercially developed systems provides adequate background for developing an automated imaging approach. Some of the key supporting concepts and technologies and their applications are presented below.

Facilities Inventory Data Collection Using Aerial Imaging

Photogrammetry and interpretation of aerial photography are well established engineering disciplines.[29] Many options exist for aerial data collection and processing techniques to establish a facilities inventory. The Army has used these techniques previously on selected installations. An example is the automated mapping system developed for the Rock Island and Redstone Arsenals by Chicago Aerial Survey, Inc. between 1981 and 1983. This project employed aerial photography (scale 1 in. = 600 ft) and stereo mapping instruments to digitize photographs. Facilities maps were then compiled by combining information from the land data base and first-hand observation from the ground. The result was an automated mapping system that uses two interconnected data bases. One data base is primarily geographic, using lines, symbols, and text common to maps; the other centers on descriptive characteristics of the facilities.

Recent work with aerial videography has demonstrated that it represents an effective tool for aerial data collection of facilities inventory.[30] The use of videography for a broad range of remote sensing and photogrammetric applications continues to increase as video camera and recorder performance and resolutions improve and equipment costs decline. Geographic information systems incorporating video input and updating capability are commercially available (e.g., the Hunter GIS, Inc., VGS-300 PLUS with GIS-Video software). Aerial visual images (either photographic or video) are also being used increasingly for interpretive evaluation of ground-based facilities. Recent studies have demonstrated the potential of aerial image interpretation to assist in earthquake resistance analysis, housing quality assessments, and dwelling unit estimates.[31] Automating the interpretation of these aerial images is also an area of intense research. Expert systems and artificial intelligence techniques are being developed that enable interpretive judgments and evaluations of aerial image content to be made by the computer. A recent publication is representative of work underway in this area.[32]

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[29] F. H. Moffitt and E. M. Mikhail, *Photogrammetry*, 3rd ed. (Harper and Row, 1980).

[30] W. A. Anderson, *Evaluating Airborne Video Image Quality and Its Potential for Remote Sensing Applications*, Ph.D. Dissertation, University of Michigan (1986); D. E. Meisner, "Fundamentals of Airborne Video Remote Sensing," *Remote Sensing of Environment*, Vol 19 (1986); D. E. Meisner and O. M. Lindstrom, "Design and Operation of a Color Infrared Aerial Video System," *Photogrammetric Engineering and Remote Sensing (May* 1985).

[31] U. P. Gauchat, D. L. Schodek, and R. Luft, *Patterns of Housing Type Density: A Basis for Analyzing Earthquake Resistance*, Final Report, NSF Grant No. PFR-780-258 (National Science Foundation, 1984); B. S. Wellar, *Generation of Housing Quality Data from Multiband Aerial Photographs*, Technical Letter NASA-119 (NASA Manned Spacecraft Center, May 1968); R. Binsell, *Dwelling Unit Estimates From Aerial Photography* (Northwestern University, Department of Geography, June 1967).

[32] D. M. McKeown, W. A. Harvey, and J. McDemott, "Rule Based Interpretation of Aerial Imagery," *IEES Transactions on Pattern Analysis and Machine Intelligence*, Vol PAMI-7 (September 1985), pp 570-585.

Facilities Condition Assessment Data Collection Using Aerial Infrared Thermography

The effectiveness of aerial infrared roof surveys in determining the extent of wet insulation in built-up roofs is well established. Tobiasson and Korhonen at the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratories (USACRREL) have conducted field demonstrations and published extensively on this subject.[33] In addition, USAEHSC has a team of engineers and equipment providing infrared roof survey support for Army installations.

Facilities Inventory and Condition Assessment Data Collection Using Ground-Based Visual Imaging and Infrared Thermography

An increasing number of facilities management organizations and real property owners are using visual imaging as a tool in a variety of applications. For several years, numerous state highway departments have maintained a "photolog" of their road lane mileage. This process involves imaging, from a moving vehicle, the entire inventory of road, appurtenances and signage that the organization has under its control. Once captured, these images are stored and used in a variety of ways by the different organizations.

Key uses of this visual information are for condition assessment of road surface and appurtenances, safety evaluations, and documentation of actual conditions. A particularly effective use of this technology has been achieved by the Connecticut Department of Transportation (CONNDOT). CONNDOT has photologged its entire road network and had the 35-mm visual information encoded on optical laser disk. CONNDOT reports a $250,000 savings in 1984 alone, much of this coming from the reduced need for field trips.[34] The Iowa Department of Transportation is currently developing a photolog system using a technology that will enable optical disk encoding of visual images directly from a video camera. The result will be a continuous video image log of highways stored on optical disk at the time of initial data collection.

A different application of similar technological concepts is found in the real estate industry, which is making increasing use of a computer data base containing images of homes for sale within a certain market. A prospective buyer can actually view the home right in the sales office.

The Massachusetts Institute of Technology (MIT) Department of Architecture uses optical disk technology to provide a visual data base of architecture of the Boston area. It has encoded numerous photographic slides of aerial and ground-based images of the area on optical disk. These are images of sections of urban areas, street perspectives and individual buildings of interest. These images comprise an architectural data base that is used for a wide range of architectural applications, including land planning, building compatibility analysis, and evaluation of existing site conditions.

Ground-based infrared thermography is another well established facilities condition assessment tool. A great deal of literature (e.g., Society of PhotoOptical Instrumentation Engineers [SPIE] publications) exists documenting uses and successful applications of ground-based infrared surveys of a wide range of facility types.[35] Energy efficiency, mechanical and electrical problems, and quality control of construction are a few examples of the broad range of applications for ground-based infrared surveys

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[33] W. Tobiasson and C. Korhonen, *Roof Moisture Surveys: Yesterday, Today and Tomorrow*, REMR-CS-1 (U.S. Army Cold Regions Research and Engineering Laboratory, September 1984).

[34] N. A. Ackerman, Ed., "CONNDOT Uses Laser Videodiscs in Photologging," *TR News* September-October 1986), pp 20-21.

[35] H. Kaplan, Ed., "Thermosense VIII, An International Conference on Thermal Infrared Sensing for Diagnostics and Control," *Proceedings of SPIE*, Vol 581 (September 1985).

of facilities. These infrared surveys have been used to find insulation problems in building envelopes, electrical transformer insulators that are overheating, steam trap diaphragms that are malfunctioning, and other facility conditions. A wide range of professional consultants in this area is available, with most employing commercially available infrared scanning equipment and analysis tools.

Optical Video Laser Disk Technology

This technology can be exploited as a tool for storage, retrieval and analysis of images in the facilities data base. It allows visual information to be stored on a video disk (typical size is 12 in. diameter by 0.1 in. thick), similar in size and shape to a phonograph album. The advantage to this technology is that it is a highly efficient storage medium, capable of storing the equivalent of 54,000 still-frame images on a single side of the disk. Another benefit is that the images can be coupled to a computer through software to provide random access capability to any image on the disk. The result is that a visual data base can be used in conjunction with other numerical and graphical data base components. This technology opens up the possibility of a wide range of applications in facilities management and condition assessment. Images stored on the video disk can also be coupled with image-processing functions to enable numerous calculations, measurements, and analyses to be performed on an image by the computer. The CONNDOT system mentioned above uses 35-mm film photography as the initial data collection tool, and has the images encoded on video laser disk by a commercial laboratory. The Iowa system under development would produce the video laser disk during data collection, employing a video camera and laser disk encoding device at the time of data collection.

Optical disk technology is expanding rapidly, with numerous new systems and applications being explored. There are many options for collecting data and encoding/retrieving images on optical video laser disks.

It should be noted that the infrared scan information referenced in the previous section is captured by the infrared sensor and initially stored on a video cassette medium. This means that the data from the infrared spectrum are displayed in a visual format that can also be encoded on the optical disk. As a result, visual images displaying information from the infrared spectrum can be stored, retrieved, and processed with optical disk technology and computer software.

Supporting Software

The basic software tools required to develop and support the automated imaging concept fall into the four major categories described below.

Relational Data Base Management Software. This type of software allows alphanumeric data about facilities to be stored, retrieved, updated and processed in a relational manner. A relational data base is one that is perceived by its users as a collection of tables. These tables represent relationships between pieces of data. Software, through the use of relational keys, can access data in the data base and display it as output in numerous formats expressing a desired relationship.[36] Several such commercial software packages exist for applications ranging from mainframe to microcomputer. Oracle (by Oracle), DBase III (by Ashton-Tate), and R:BASE 5000 (by Microrim) are some examples. Relational data base software customized specifically for facilities management applications is also commercially available (Knowledgeman is an example).

The data base management software used for IFS-M is Oracle. At the installation and facility levels, the data base contains information such as the total number of facilities on an installation, the

[36] C. J. Date, *An Introduction to Database Systems*, Vol I, 4th ed. (Addison-Wesley 1986), pp 96-245.

type of facilities, and their locations. These levels would also store basic information concerning individual facilities such as square footages, material types (brick, wood, asphalt), general condition and performance codes, major component inspection frequencies, overall maintenance expenditures, and facility replacement cost estimates. At the facility and component levels (EMS), the data base would contain more detailed information including facility component and equipment inventories, inspection methodologies and individual component condition data. The data base management software used for the EMSs is DBase or R:BASE (various versions).

Geographic Information Systems Software. This software allows graphically oriented data (lines, polygons, vectors, symbols) to be digitized and stored in a data base. Alphanumeric data relating to the geographic information can also be integrated into the system. Examples of outputs are mappings of facilities and topographic maps with contour lines. Facility data can be linked to the maps relationally, allowing data such as building equipment inventories and inspection records to be displayed on the map with a facility. Packages of this type are also available for the full range of computer sizes, from mainframes to micros.

Architectural Line Drawing Software (Computer-Aided Drafting [CAD] Systems). This software allows graphically oriented line drawing information to be entered, stored, retrieved, updated and integrated with other components of the data base. These systems store plans, elevations and other graphically descriptive information about facilities on a detailed level. A wide variety of CAD systems is available for applications ranging from mainframes to micros.

Software Integrating Visual Information Stored on Optical Disk With Other Data Base Components. This software supports information access from optical disk to be used in conjunction with other components of the data base. These products range from microcomputer-based systems that retrieve a single frame at a time to mainframe and mini-based systems that permit optical disk encoding, data compression, filing, editing, printing, and updating to be completed in a single location using a series of workstations. These sophisticated systems also allow other relational data base information to be integrated, displayed, and edited with the image information. An example of such a system which is commercially available is FileNet, marketed by FileNet, Inc.

Image-Processing Software Tools. A major goal of the automated imaging concept is to improve the quality and comprehensiveness of visual inspections. Automated imaging can achieve this goal in two ways. The first is by allowing inspections to be completed more efficiently and automating the inspection process itself. One example of this function is bringing the required inspection information for a large number of facilities to an inspector at a single workstation. The second way of improving the quality of inspections is by providing additional tools for analyzing visual inspection information.

One of the strengths of the automating imaging concept is its ability to enable visual and infrared information to be viewed and analyzed together. This analytical capability relies on image-processing tools. "Image processing" refers to the use of a computer and specialized software to extract useful numerical and symbolic information from an image. Many different types of images can be analyzed in this way, and a variety of input formats can be used, ranging from standard videotape to satellite data on magnetic tape. The fundamental process involves digitizing the initial image by assigning brightness values to a coordinate system imposed on the image, and then storing these values in digital format in the computer. Once this digitizing is completed and numerical brightness values are assigned to discrete picture cells defined for the image, these data can be processed in many different ways to aid in analyzing the image. Some examples are calculations of areas of interest within an image and enhancement and detection of edges.

Pattern recognition techniques allow the properties of a given scene in an image to be compared with a known model for identification and correlation of objects. Once again, a wide variety of software packages for this type of analysis is available. An example of a minicomputer-based system

is the VISTA-IPS package sold by Logica Corporation. A microcomputer-based package example is the MaxVision system marketed by DataCube. Harnessing this type of image processing is an active field of research in facilities condition assessment. The National Bureau of Standards has conducted research on a minicomputer-based system to evaluate deterioration of certain types of building materials.[37] Other applications research is underway.[38]

It is clear that the basic technologies required to implement automated imaging in facilities management have been developed. Applying these technologies to meet Army facility management needs will primarily involve selection, adaption, and integration of existing technology rather than development of new technology. Based on these findings, USACERL has developed three complementary concepts. These concepts, and their supporting technologies, are described in the following section.

Concepts Applicable to Army Facilities

Overhead Images of Installation Facilities Using Aerial Photogrammetry Techniques

Aerial video and infrared imaging from fixed-wing aircraft or helicopters represent the first of the three proposed concepts. This procedure would provide images of buildings and other above-ground facilities on a scale of approximately 1 in. equal to 50 ft. Ground coverages for these images would be on the order of 100,000 to 1,000,000 sq ft. Visual data from these images could be used for identifying facility size and type, locating roadways or ponding on roofs, and determining the nature of ground cover. Infrared images provide information on thermal anomalies present in built-up roofing. The imaging of an installation at this level of detail could be completed in 1 or 2 days. It is anticipated that aerial imaging would be done no more than once a year and no less than once every 5 years. These aerial images would contain a large volume of useful information in several related areas:

Facility Inventory--basic inventory data could show the facility type, size, and height, and material types.

Facility Mapping--aerial images from the visual spectrum could be used with geographic mapping systems to provide automated geographic mapping of an installation. One such system is the Geographic Resources Analysis Support System (GRASS) developed by USACERL.[39] GRASS, in part, includes a subsystem that displays geo-references and compares and classifies aerial photogrammetry and satellite images.

Facility Condition--extensive condition information could be obtained from images of facilities at a scale of 1 in. equal to 30 ft. Using both the visual and infrared images, roof condition, painting, exterior siding, and brick condition information would all be obtained.

A key to the usefulness of the information listed above is that it can be collected in digital format, stored on optical disks, and accessed directly by computers. This visual and infrared image data base

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[37] J. W. Martin, M. E. McKnight, and D. P. Bentz, *A Computer Image Processing System for Quantitative Evaluating Degradation in Building Materials* (National Bureau of Standards, Center for Building Technology, 1985).

[38] C. Harris-Stewart, "Imaging System Detects Failures in Coating Early," *Engineering News Record* (September 3, 1987), p 12.

[39] *GRASS Users and Programmers Manual for the Geographical Resources Analysis Support System (GRASS 3.0)*, ADP Report N-87/22 (USACERL, Revised September 1988).

could be coupled by computer to numerical inventory and condition data. Computer image processing could be developed that would automate the interpretation of this visual data. The airborne visual and infrared data would support installation-level information needs. It would provide information on overall facility inventory, size, location, spatial relationships, and general condition data. It is proposed that the information be used in a minicomputer environment with a workstation such as that planned for IFS-M. Research is underway to integrate IFS-M and GRASS.

Ground-Based Images of Installation Facilities

This second concept would involve using a video camera coupled with an infrared scanner to image facilities from the ground level. This procedure could be done from a vehicle at low speeds or on foot, as required. The information thus obtained would be similar to the aerial work, but would provide much greater detail. These images would have a scale on the order of 1 in. equal to 5 ft. Information extractable from these images is exterior facade material types, individual component types, edges between material types, and surface distress such as cracking and peeling. Inspectors at a workstation would be able to simultaneously access aerial and ground-based images to evaluate conditions of the roof exterior facade, windows, foundation, and exterior grounds. Also provided from this "horizontal" image information would be material quantities, sizes, and types. The video scan can be coupled with an infrared scan to provide a greater level of condition information (e.g., heat loss and leakage). The workstation concept also allows pertinent existing information in the data base for a facility to be used in conjunction with the visual record being evaluated. Computer image processing could be coupled with this horizontal record as well to allow automated inventory and comparison. At the very least, this information would enable inspectors to develop more detailed priorities for deciding which facilities to inspect first on an installation. Developed to its full potential, this information could be used to greatly reduce inspection time required at facilities and provide more information than is now being gathered.

Research is in progress to integrate IFS-M and EMS. It is anticipated that this information would be stored in the minicomputer environment at the installation level (IFS-M) and the microcomputer facility EMS level (i.e., BUILDER). Installation-level managers would use the information to support maintenance decisions such as which buildings need new siding, or which homes will be renovated. Facility-level component inspectors would use the information to manage and prioritize facility inspections and to conduct preliminary visual inspections at a computer workstation. This function would require that the visual and infrared data be capable of integration with component-level EMSs such as ROOFER.

Detailed Interior Images of Installation Facilities

The objective of this third imaging concept is to establish a detailed data base of images from the visible and infrared spectra for the interior of a facility and its equipment. Information on conditions such as cracks in walls, water stains, peeling paint, and leaking pipes is extractable from this type of image. The images would be captured in such a way that the component's relationship to its environment can be understood.

In general, this procedure would require a facility space to be imaged as a whole, with individual key components being zoomed in or imaged from close range. For a general view of a room or facility space, an individual image will represent approximately 200 to 1000 sq ft. For more detailed, close-up images, the area represented will be on the order of 0.1 to 10 sq ft. This data collection is envisioned as being completed in conjunction with a detailed facilities inventory in which a complete walk-through of the facility is conducted, with each room or space being delineated and the key components and equipment items identified for each space. The data collection would require one technician using an automated inspection cart (discussed in Chapter 6). Detailed facilities inventory and condition information would be obtained rapidly using the sensors on the cart. The two-wheeled

cart would hold a portable computer, ultrasonic distance measurement device, bar code facility/equipment inventory coding, video camera/infrared scanner, and portable synchronized video cassette recorder. The technician would move from space to space in a facility, imaging and encoding inventory and condition data. The result of this data collection effort would be a continuous stream of video images from the visual and infrared spectra detailing the interior surfaces, doors, windows, equipment and fixtures for the facility.

This information would again be stored digitally and used in conjunction with other elements in the facilities data base. It is anticipated that this visual and infrared information would reside in the minicomputer with other components of the IFS-M data base. The images would be stored on optical disk with a file structure, allowing them to be referenced according to the facilities in which they are contained. Relational keys would also permit the information to be accessed based on component types, inspection frequencies, or other criteria. This information could be integrated with the facility- and component-level EMSs. In this way, an inspector using an EMS such as ROOFER could use visual and infrared images of a built-up roof to provide the inspection data required. Integrating this detailed imaging inventory and condition information into the facilities data base provides a means of:

1. Enabling experienced inspectors to view problem areas before actual site visits.

2. Establishing a visual and infrared image data base of facility interiors and equipment that could be used for current and future condition assessment.

3. Allowing operations staff to actually "see" the equipment or space they are to service when going on a service call or work order.

4. Creating a permanent record of how an item or area looked on a specific date to aid in project documentation and justification.

5. Performing detailed energy audits on facilities.

6. Permitting space planners to view facilities from a workstation to determine preliminary allocation suitability.

7. Allowing estimations and planning functions to be performed at a workstation, with the complete facilities data base available to the estimator for reference.

Concept Summary

The three-part concept presented above addresses the inventory and condition assessment needs identified in Chapter 4. Additional rationale for the automated imaging concept can be seen in the following points:

1. The overwhelming majority of inspections done at the installation level are visual.

2. Due to resource constraints, there are not enough trained component inspectors (in-house or contract) to visit and inspect all facilities on a regular basis.

3. There would be a high "value added" effect for component inspections and other DEH functions by creating a visual and infrared image data base of facilities along with other facility information contained in the IFS-M, GRASS, and EMS data bases. This value-added effect stems from the added quality of inspection gained, as well as the analysis and potential use of the information.

4. This online information would allow a significant amount of condition assessment to be done at a workstation integrated into IFS-M, GRASS, and EMS.

5. This data base of visual and infrared information could be used by component inspectors for "manual" evaluation of components by viewing stored images. Reports would be entered through online windows directly into the data base.

6. This data base of visual information could also be coupled with image-processing functions to provide automated evaluations of large "homogenous" facilities (e.g., pavements, siding).

The following section is an example illustrating a potential application for the automated imaging concept.

Example of a Potential Application

This example will use a hypothetical Army installation with an area of 200 sq mi (10 mi wide by 20 mi long) containing 1000 facilities. Twenty-five percent of the installation area is undeveloped. Suppose that the installation's facilities managers are holding their annual M&R budget and planning meeting. The installation has been assigned a new division of troops and must rehabilitate its inventory of single-story wooden troop housing, most of which has deteriorated siding and shingles. The housing must be prepared in accordance with military regulations, which include a specific standard for wooden siding and roofing shingles. The managers have been given an overall repair budget for this work. Prior to the meeting, facility inspectors were assigned to evaluate the needed repairs and estimate the cost of the work. It is known before the meeting that the inspectors' estimates for repair costs are much higher than the budget available. A major purpose of the meeting is to decide a course of action for barracks repair in the coming year.

To develop their estimates, inspectors used the integrated facilities data base workstations. Geographical information from GRASS was used to establish where the barracks buildings were located, how many were there, and what sizes they were. Numerical information related to each of the buildings was also used. The areas of siding and shingles involved, their previous repair and service records, and siding and shingle material specifications were displayed with the geographical data. Ground-based images of the elevations of each barracks were then displayed and a visual assessment of siding and shingle condition was made. Areas considered deficient were interactively marked on the video monitor using a mouse. Area calculations and cost estimates were done automatically by the computer using the interactively established video data and unit costs for siding and shingle repair work entered previously. The result was a cost estimate for the repair of each barracks and a cumulative estimate stored in the numerical component of the data base. These data are also indexed geographically, so they can be displayed with geographical or visual data.

At the budget meeting, managers use the workstation to display the barracks geographically along with the related repair estimates. Images of the barracks are reviewed to establish agreement that the inspectors' interpretations of deficient items were accurate. Siding and roofing service order work is reviewed to see if some of the buildings have major problems while others function satisfactorily. Some of the less deteriorated buildings in remote locations are determined as not high-priority repairs and are removed from the estimate. Potential barracks occupancies are then accessed from the numerical data base to establish which repairs could be made at the lowest "per occupant cost." Estimates are summed starting with the lowest value and moving incrementally upward until housing for the entire division is determined. This value is compared with repairing the buildings based on optimal geography--some of the buildings are in inconvenient locations and others are by the front gate and appearance is a morale consideration.

After considerable debate, an "optimal" plan is reached. Specific barracks buildings are identified as needing repair and a sequence and schedule for the work are established. The work requirements were entered into the facilities data base during the meeting. This step resulted in the siding and repair work being automatically included in the overall facilities work plan and budget for the year. Due to this automation, operations personnel at other levels in the system (estimators, project managers, shop technicians) are updated with the changing requirements.

The concept and scenario envisioned above is based on implementation of imaging technology that has already been developed in other applications. The next chapter describes how selected technologies would be integrated to develop such a system.

6 AN AUTOMATED IMAGING SYSTEM FOR FACILITIES MANAGEMENT

The three major components of the automated imaging concept presented in Chapter 5 are described in further detail in this chapter. Each component is described in terms of data collection, transfer into the facilities management system, and integration into the facilities management data base.

Aerial Imaging

Data Collection

The initial data collection for the aerial imaging system requires the following key equipment items:

- Aircraft--a standard fixed-wing single-engine aircraft.
- Video camera--electronically shuttered video camera with a shutter speed of 0.001 sec or faster (e.g., the Panasonic D 5000).
- Infrared scanner--a device with a transducer capable of detecting the radiance of a material in the infrared spectrum. This difference in radiance can be used to detect thermal anomalies. The Inframetrics 600 and Agema TR 870 are examples of scanners.
- Portable video cassette recorder (e.g., Panasonic VHS AG-2400)
- Standard VHS video cassette tapes.

The method of data collection uses imaging from an aerial flyover of the installation. The video camera is installed looking downward from the bottom of the aircraft. The video camera and infrared scanner are both positioned with the sensor in vertical alignment, and the field of view of the scanner is made to be equivalent to the camera. Both the video camera and infrared scanner are connected to video cassette recorders. The initial images are taken with a vertical camera alignment. The aircraft flies over the base at an altitude of 3000 to 3500 ft, capturing a ground image width of approximately 440 yd with each pass. With a camera focal length of approximately 1.25 in. (20 mm), a minimum resolution of approximately 6.5 ft will result. The installation is imaged completely, with parallel flight lines chosen to ensure full capture of the installation's entire ground surface. This vertical data capture process follows the same fundamental photogrammetric principles as standard aerial photogrammetry employing photographic film and a shuttered camera. Oblique aerial video is then obtained following the vertical work. The purpose of the oblique video is to be able to view exterior wall surfaces, facades, and other vertical elements of facilities. Again, this oblique video imagery is obtained using standard photogrammetric principles. The final product obtained from this data collection is two sets of video cassette tapes from each sensor. The first set is a continuous aerial view of the installation looking straight down at its facilities providing a vertically aligned visual and infrared image. The second set of tapes is a continuous aerial view from the visual and infrared spectra of the facades and side elevations of facilities, taken from an oblique angle.

An estimate for the cost of an aerial video survey for an installation with an area of 200 sq mi (10 mi by 20 mi), 75 percent of which is developed, with a total of 1000 facilities, would be as follows. Assuming a lateral ground coverage of 440 yd per pass, forty 20-mi passes are required to cover the entire base. This means the total distance requirement for full coverage is 800 mi (40 passes 20 mi long). Add 20 percent to this figure for turns and in-flight adjustments, and the mileage required becomes approximately 1000. Assuming a flight speed average of 100 mph results in a flight

time of 10 hr. At $400/hr for the aircraft, the cost for the flying involved in the vertical video survey is $4000.

The cost of flying the oblique work also assumes a ground coverage of four passes to the mile and a flight speed of 100 mph, but adds a 40 percent mileage factor for turns and in-flight adjustments. Thus, the total mileage requirement is 1120 mi. This figure translates into 11 hr of flying, for a flight cost of $4400. The total flight costs are $8400 for both the vertical and oblique work. The price of the video camera is $1500. Conventional portable video cassette recorders are $800 each, making the cost for two $1600. The infrared scanner costs $30,000. The cost of the 12 videotapes required for 11 hr of flying is about $60.

The total costs for the aerial data collection described above can be summarized as follows:

Initial Equipment Costs

Video camera:	$1,500
Infrared scanner:	$30,000
Video cassette recorders:	$1,600
Total initial equipment costs:	$33,100

Recurring Costs for Aerial Data Collection

Aircraft flight costs:	$8,400
Videotapes:	$60
Total costs for aerial data collection:	$8,460

Hardware/Software Interface From Video Cassette Tapes to the Facilities Data Base

The power of the proposed system to assist in maintenance inspection comes from its ability to translate the analog images on videotape into a digital format for storage and integration into the facilities data base. The digitized aerial visual information could be stored on optical disk and used as a component of the facilities data base within IFS-M or the appropriate EMS.

VCR data can be digitized for use with the computer in several different ways. Individual frames from the VCR can be "grabbed" manually, digitized, and stored in a file arranged and sequenced according to specific application needs. Or, the VCR can be played directly into digitizing boards resident on a micro- or minicomputer. The audio track of the VCR can be encoded to act as a "trigger" identifying frames of interest for automated digitizing. The encoding can be based on a time interval with key data encoded on the tape (e.g., geographic position, time, altitude) every time a specified time interval elapses. With such a system, the storage requirements can be estimated based on the following assumptions:

- Encoding is set at a 3-sec interval.
- The area of ground coverage imaged is 1320 ft by 990 ft (the same 440-yd swath used above assuming an aspect ratio of 4 to 3).
- A 3-sec trigger interval with the ground coverage assumed above and an air speed of 100 mph results in full ground coverage with an image overlap per frame of 50 percent.
- Both video and infrared images are to be digitized, indexed, and stored on optical disks.

These assumptions lead to an estimate of 22 hr of continuous video images, or 22 hr x 60 min/hr x 60 sec/min = 79,200 sec. With a digitizing requirement of two frames (video and infrared) every 3 sec, there are a total of 52,800 frames to be digitized (assuming a 240 x 512 pixel representation). This creates a storage requirement of 52,800 frames x 240 x 512 = 6.5 x 10^9 bytes (assuming 8-bit pixels). Using optical disks with a storage capacity of 2.6 10^9 bytes per disk, the result is a disk requirement of 2.5.

The product of this digitization and optical encoding is an indexed and filed sequence of aerial images of an installation's facilities, able to be recalled through the computer's RAM. This configuration allows the images to be used in conjunction with other components of the IFS-M and EMS relational data bases. It is envisioned that the images would be filed by geographic location initially. However, the file structure could be set up in a number of different formats.

Several components are required for creating and accessing the video-encoded aerial images. The first is a standard VCR for playback of the taped data. The second is a "frame grabber" or digitizer installed in a mini- or microcomputer. This second component translates the images on the videotapes into digital format, which can be computer-processed. A third component is the hardware required for encoding the digitized images on optical disk. These optical encoders are available as units linked to a minicomputer system (FileNet Corp. markets a product for business office environments which uses the required technologies).[40] It is projected that the most efficient configuration for the Army would be to establish a single or small number of optical disk encoding centers. VCR data would be sent to these centers. The encoding could also be contracted to commercial laboratories. 3M Corporation currently provides such a service. The product resulting from this encoding is a collection of optical disks* similar in size and shape to a phonograph album. Encoded on the disks are digital images that can be recalled and played back continuously or viewed individually as separate pictures.

A fourth component couples a collection of optical disks to the computer through software to provide random access ability. The number of disks required to store the needed facility images will vary depending on the base size. The most efficient way to handle multiple disks is to use an optical disk library with an image server. This type of system is composed of a peripheral device that provides the optical disk storage function. These systems are available commercially. FileNet markets a system called the OSAR library, an automated, robot-like jukebox that loads and unloads optical disk cartridges to and from optical disk drives.[41] The FileNet OSAR library system supports either 64 or 204 optical cartridges, and up to four optical disk drives. Other companies also market disk library systems. It is estimated that the cost of tying an optical disk library of 64 disks or more into a minicomputer system such as the one envisioned for IFS-M would cost in the range of $100,000 to $200,000 per installation. If the minicomputer that houses IFS-M or an available IBM-AT equivalent microcomputer is used, no additional costs are necessary for computer hardware. If this is not possible because of other computer uses, one would have to be purchased.

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[40] W. Fisher and J. Gilbert, "FileNet: A Distributed System Supporting Workflo: A Flexible Office Procedures Control Language," presented at the Institute of Electrical and Electronics Engineers (IEEE) Computer Society Symposium, Gaithersburg, MD (April 1987).

[41] W. Fisher and J. Gilbert.

* A 12 in. double-sided disk can store about 1.3 billion bytes per side, and other sizes are available.

The cost for the components described above will vary depending on the size of the installation and the amount of information to be digitized and stored. A conceptual guideline, using the installation characteristics from the previous section as an example, is:

Digitizing system (hardware and software):	$ 15,000
Optical encoding device:	$150,000
Optical disk library storage/server:	$150,000
Microcomputer:	$ 10,000
Total hardware cost for optical encoding and storage	$325,000

To summarize, the transformation from a continuous stream of aerial video imagery captured on VCR tape to digital information used for constructing a facilities data base requires the following key elements:

- A minicomputer such as the Unisys 5000-80 or a microcomputer such as the IBM-AT.
- Video cassette recorder (e.g., Panasonic VHS AG-2400).
- Optical disks--12-in. doubled-sided with total storage of 2.6 Gb.
- Optical disk player.
- Optical disk encoding capability--either send out to commercial lab or use a device such as the FileNet scanner.
- Optical disk library--either a manually managed library with a small number of disks or an automated jukebox system such as the FileNet OSAR library.

The endproduct of this transformation from tape to digital medium is a data base of images from both the visual and infrared spectra stored on optical disk and filed in such a way as to enable almost instantaneous recall through the computer's RAM. The file structure and method of recall can be customized to a specific application. It is expected that aerial images would initially be filed according to geographic coordinates.

Ground-Level Imaging

Data Collection

The initial data collection for ground-level imaging requires the following key equipment:

- Vehicle--a two-passenger car, van, or other vehicle capable of traveling at posted speed limits with the passenger side open to allow video/infrared imaging of the full height of facilities.
- Video camera/infrared scanner--the instrument proposed couples a video camera and infrared scanner together. A single viewfinder would be used, with the camera and scanner lenses focused on the same point with the same field of view. The video camera would operate as a standard model, with electronic shuttering and a shutter speed of 0.001 sec or faster (e.g., Panasonic D5000). The infrared scanner would operate as a normal unit, recording on standard VHS tape (the camera's performance must be equivalent to the Inframetrics 600). The

camera/scanner instrument would produce two separate streams of data, each recording to a separate but synchronized tape.

- Portable synchronized video cassette recorder--must receive two incoming streams of video input, synchronize them, and record them on either a single cassette tape or two separate video cassette tapes.

- Standard VHS video cassette tapes.

The objective of ground-level data collection is to obtain a data base of images from the visual and infrared spectra on the ground for the exterior facility inventory. Inventory and condition information will be integrated and correlated with the existing facilities data base. To accomplish this task, each above-ground facility is imaged with the video camera and infrared scanner. It is proposed that the video camera and infrared scanner be coupled in such a way as to enable them to be used from a person's shoulder or from a tripod or fixed mount. Each of a facility's elevations would be imaged at a scale that would allow features of interest to be determined (e.g., windows, doors, condition of siding, landscaping). In some cases, this imaging can be done directly from the vehicle; in other cases, the facility must be taped on foot. The distance from the building for basic imaging would be in the range of 30 to 60 ft. Specific features of interest (e.g., deterioration) can be zoomed. As the buildings are being taped, the elevation, orientation, and name are encoded on the tape. Audio notes can also be made in conjunction with the visual record. The result of this effort is a series of images from both the visual and infrared spectra showing the exterior of all above-ground facilities with the images encoded to describe the location, date, and time of acquisition for each elevation.

Using the same installation proposed for the aerial work, a conceptual estimate for the cost of data collection for ground-based exterior imaging can be developed using the following assumptions:

- 1000 facilities are to be surveyed.

- The survey requires 10 min per facility.

These assumptions result in 170 manhours for completing the video work; at $50/hr, the cost is $8500. Adding an extra 10 percent for setup and closeout, the total labor costs for the ground-based imaging becomes $9350. The combination video/infrared camera would be a custom item, as would the portable synchronized recorder. Assuming 7.5 minutes per building of actual video time, the number of tapes required would be 7500 min/120 min tape = 62.5 videotapes x 2 = 125 tapes, at $10/tape = $1250 for tapes.

The total costs for ground-based exterior survey can be summarized as follows:

Initial equipment costs*

Video/infrared scanning device:	$35,000
Portable synchronized video cassette recorder:	$10,000
Total initial equipment costs:	$45,000

* Note: this equipment could be used for the initial aerial data collection as well, instead of the standard video and infrared scanner. Assuming this were the case, the initial equipment costs for the ground-based survey would be zero.

Recurring Costs for Each Ground-Based Exterior Survey

Labor:	$9,350
Transportation:	$3,500
Tapes:	$1,250
Total recurring costs:	$14,100

Hardware/Software Interface From Videotapes to Facilities Data Base

Once again, the power and usefulness of the ground-based information lies in its ability to be translated into a digital format and used in a facilities data base. The hardware and software required to translate the cassette tape data onto optical disk is identical in this case to that required for the aerial data collection. The option exists again to manually digitize frames of interest by viewing the tapes, grabbing frames, and having them digitized. It is also possible to trigger the digitization process automatically. This procedure could be done on a time interval as described for the aerial work. Or, a technician could do the triggering while the imaging is being completed in the field. The triggering mechanism could be an electronic pulse encoded on one of the audio channels on the cassette tapes. The trigger would be a pushbutton that the technician would depress when an image appears in the viewfinder which he or she is confident belongs in the visual data base. A single frame or a set number of frames after the trigger impulse would be digitized.

Using the model installation with 1000 facilities, and assuming a maximum of 250 images to be digitized per facility, a total of 250,000 frames must be digitized. The number of 8-bit pixels per image is $240 \times 512 = 1.288 \times 10^5$, yielding a digitization requirement of $250{,}000 \times 1.288 \times 10^5 = 3.22 \times 10^{10}$, or 32.2 gigabytes. Assuming optical disks with storage of 2.6×10^9, the result is a requirement of 13 optical disks.

Detailed Interior Imaging

Data Collection

Key equipment required for the detailed interior imaging is:

- Video camera/infrared scanner--the same instrument as proposed for the ground-based exterior imaging.
- Portable synchronized video cassette recorder--the same recorder as described for the ground-based exterior imaging.
- Hand-held portable computer--the MicroWand by Hand-Held Products is an example.
- Ultrasonic distance measurement device--the "Rangescanner" by Exergen is an example.
- Hand-held optical bar code scanner--this is coupled with the hand-held computer.
- Electronic "clipboard"--includes bar-coded equipment identifiers for rapid scanning entry of equipment in each space.

This equipment could be purchased directly by the Army and used by its own personnel either on individual installations or by regional teams using the equipment on a number of installations. The services and equipment could also be contracted from an outside facilities management consultant.

The objective of this imaging is to establish a detailed data base of images from the visual and infrared spectra for the interior of a facility and its equipment. This data collection is envisioned as being completed in conjunction with a detailed facilities inventory in which a complete walk-through of a facility is conducted, with each room or space being delineated and the key components and equipment items identified for each space. The data collection would require one technician using an automated inspection cart such as that shown in Figure 12. The two-wheeled cart holds a portable computer, ultrasonic distance measurement device, bar code facility/equipment inventory coding, video camera/infrared scanner, and portable synchronized video cassette recorder. The technician is responsible for entering the room number (or some other space designation), its area using the distance measurement device, and the equipment present in the room using the bar codes and optical scanner. The video camera/infrared scanner are used to encode the room number on the tape and image the walls, ceiling, floors, and equipment. If the equipment serial numbers are accessible, these are also imaged. The technician also uses the audio track of the VCR to record notes concerning room and equipment condition. As the technician moves to the next room, the encoding process is repeated and the inventory and inspection process continues. The result of this data collection effort is a continuous stream of video images detailing the interior surfaces, doors, windows, equipment, and fixtures for the facility.

Facilities management consultants working on inventory and maintenance systems have developed the computer-based inventory system with bar coding and optical scanner to the point that a technician can inventory an average of 35,000 sq ft of enclosed facility area in an 8-hr day. It is reasonable to assume that the technician with the video camera described above can maintain the same rate. The average installation has approximately 1000 buildings and the average enclosed space is nearly 6000 sq ft.[42] Thus, there is a total of 6,000,000 sq ft on an installation. The number of technician mandays required to collect data for this number of square feet is 6,000,000 sq ft/35,000 sq ft/day = 171 days. The labor cost labor would be $50/hr/technician x 8 hr/day x 171 days = $68,000. The cost of equipment for one technician would be:

- Video camera/infrared scanner--included with ground-based exterior equipment.
- Portable synchronized video cassette recorder--included with ground-based exterior equipment.
- Portable computer with optical scanner--$2000.
- Bar code development--$3000.
- Ultrasonic measurement device--$1500.
- Cassette tapes--$13,680 (1368 hr/2 hr/tape = 684 tapes x 2 = 1368 tapes x $10/tape).

The total costs for detailed interior imaging for an average sized installation can be summarized as follows:

Initial Equipment Costs	
Portable computer with optical scanner:	$2,000
Bar code (development/production)	$3,000
Ultrasonic measurement device	$1,500
Total equipment costs	$6,500

[42] *Facilities Engineering and Housing Annual Summary of Operations Report* (Directorate of Military Programs, Office of the Assistant Chief of Engineers, 1986).

Recurring Costs	
Labor:	$68,000
Cassette tapes:	$13,680
Total recurring costs:	$69,368

Hardware/Software Interface From Video Cassettes to Facilities Data Base

This interface involves essentially the same hardware as the previously described ground-based exterior imaging. The continuous stream of video images recorded on the tape can be sampled and digitized manually or automatically using a trigger as described in the ground-based exterior section.

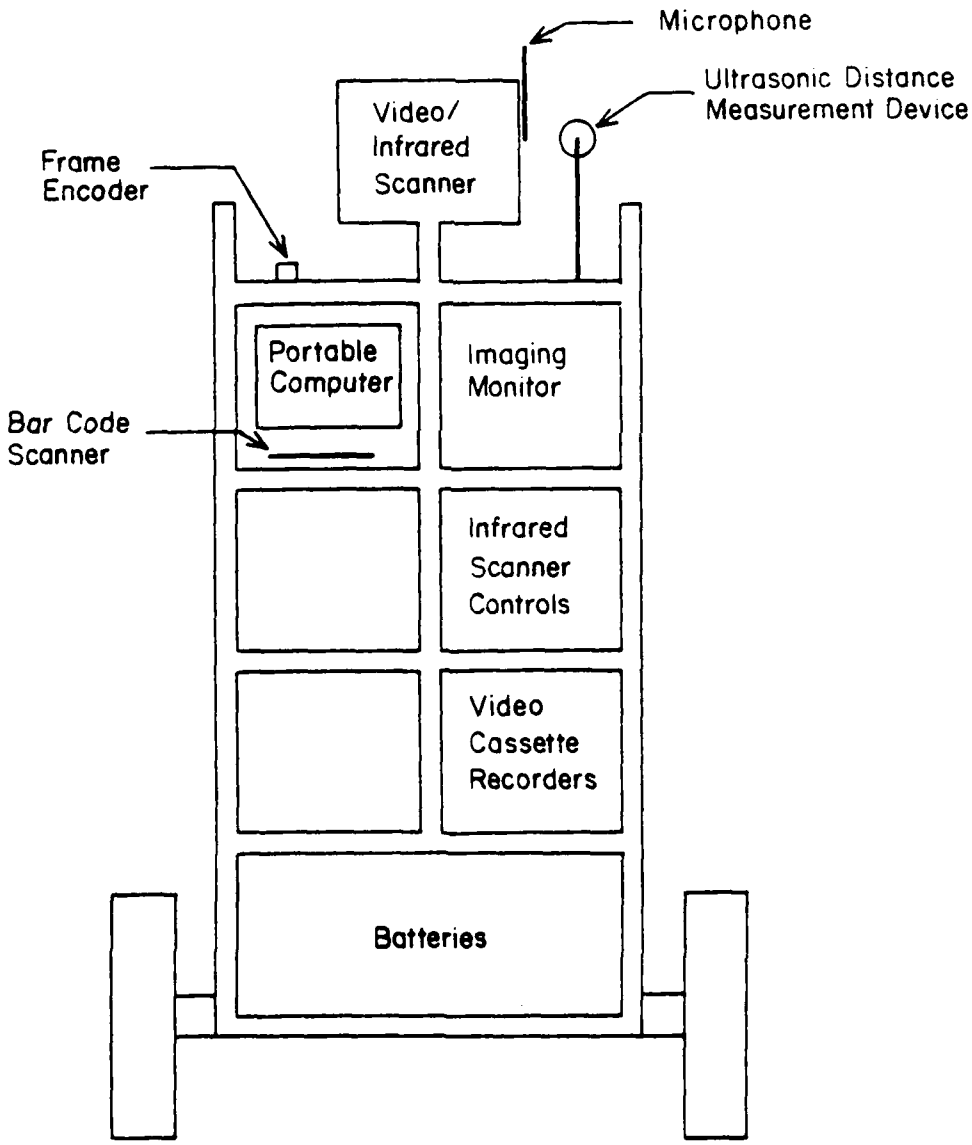

Figure 12. The detailed interior imaging cart: concept.

Using the trigger allows the cassette tapes of images to be played back on the VCR through a frame grabber/digitizing system coupled with a mini- or microcomputer. This digitizing process is the same as described earlier. The result of digitizing is a series of images, including room or space designations, capable of being encoded on optical disk. Encoding on optical disk is handled with the same hardware as described in the aerial imaging section earlier. Initially this sampling is envisioned as being done manually, with a technician viewing the tape, "grabbing" a frame of interest, identifying it as a frame to be digitized, actually digitizing it, and storing the digitized result on optical disk. This is assumed to be a technician-level function, with the goal being to identify clear shots of floors, walls, doors, windows, and equipment present in a room or space. The result of this sampling process would be a series of digitized images, with the room number, time, and date encoded on the image. These images would be arranged in sequence on optical disks and recalled from RAM in conjunction with standard numerical, geographical, or drafting software packages. The original video cassette tapes can be used for more detailed analysis and reference for specific areas of interest.

The data requirements for this type of imaging can be estimated as follows. Assuming 6,000,000 sq ft of enclosed space on the installation, 27,000,000 sq ft of interior surface area will be imaged. Assuming an average image size of 50 sq ft, this requires 0.54×10^6 images. With 1.288×10^5 8-bit pixels per image, a total storage capacity of 0.7×10^{11} bytes is required. This much storage would require $0.7 \times 10^{11}/2.6 \times 10^9$ bytes/disk = 27 disks.

Integration of the Visual and Infrared Images Into the Facilities Data Base

The preceding sections described the hardware and software required to establish a visual and infrared image data base to be used in conjunction with the IFS-M data base. Having established these image data bases in digital form, it is now primarily a matter of selecting software to integrate the systems. It is envisioned that the aerial, ground-based, and detailed interior image components of the data base will be maintained as an independent module connected to IFS-M. This would enable the images to be stored efficiently and used for a variety of installation-level management decisions, and to be accessible to EMS users. As discussed earlier, EMS data bases are also expected to be components of IFS-M. With this arrangement, important facilities data can be maintained at the IFS-M level and be made available to a variety of specific EMS user needs. Simultaneously, access to EMS data bases will make detailed EMS data available "up the line" to more global IFS-M user needs. Figure 13 is a flowchart of how such an integrated data base concept would be structured.

The point at which the hardware and software would come together is the workstation. Coupled to an integrated data base, the workstation would enable a maintenance manager or component inspector to sit at a bit-mapped computer terminal or PC equipped with a standard monitor and do the following:

- View a geographic map of all major above-ground facilities on an installation (or sections of the installation displayed in more detail).
- View the same geographic information with numerical data for facilities displayed with the facility.
- Highlight facilities on the map that have certain characteristics (e.g., inspections due this month, material of a certain type).
- Display construction drawings relating to facilities of interest either on a split screen with other data simultaneously or on a single screen.
- Display actual aerial images of facilities or sections of the installation--again on a split screen with other data or on full screen.

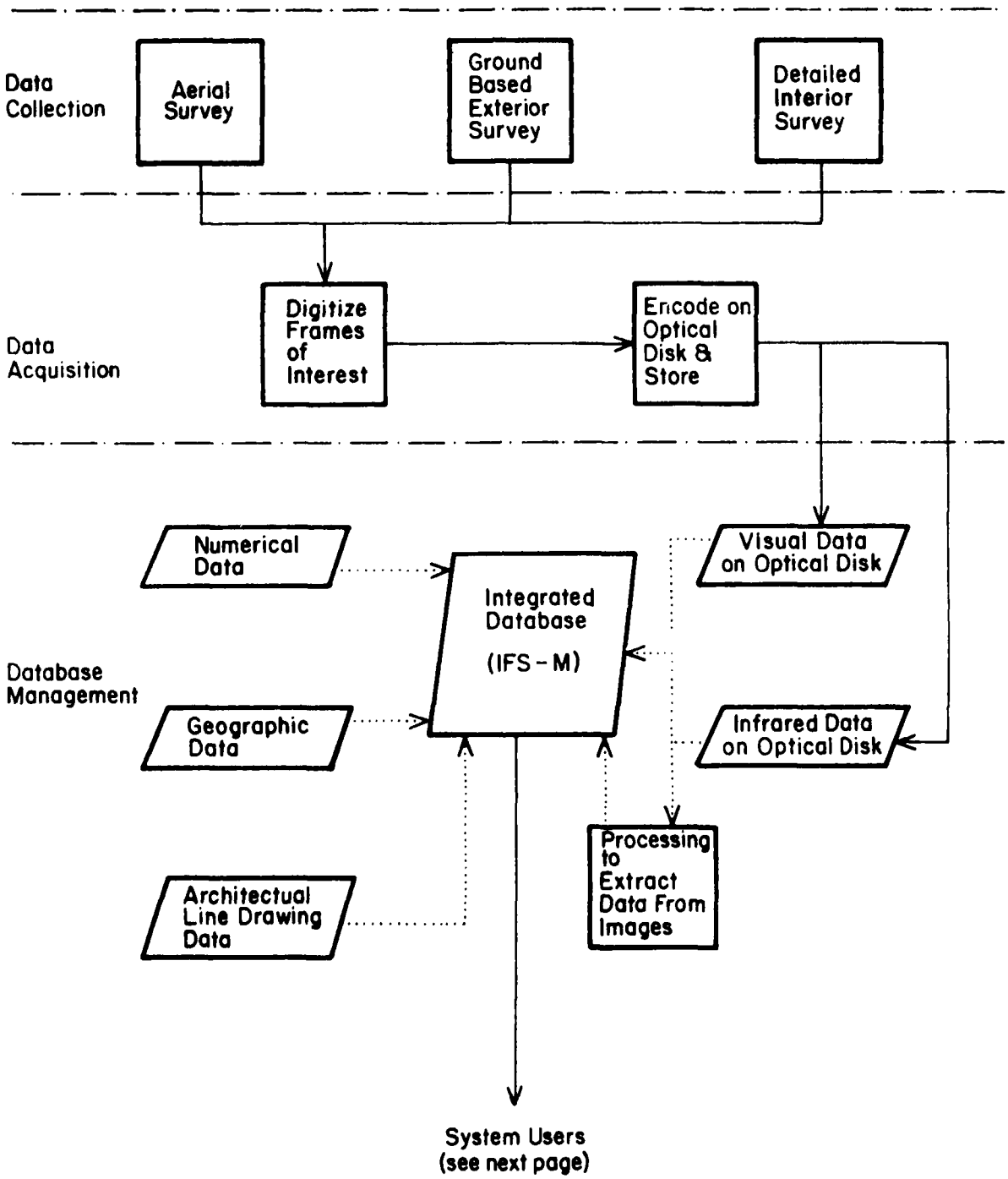

Figure 13. Flowchart of integrated facility data base.

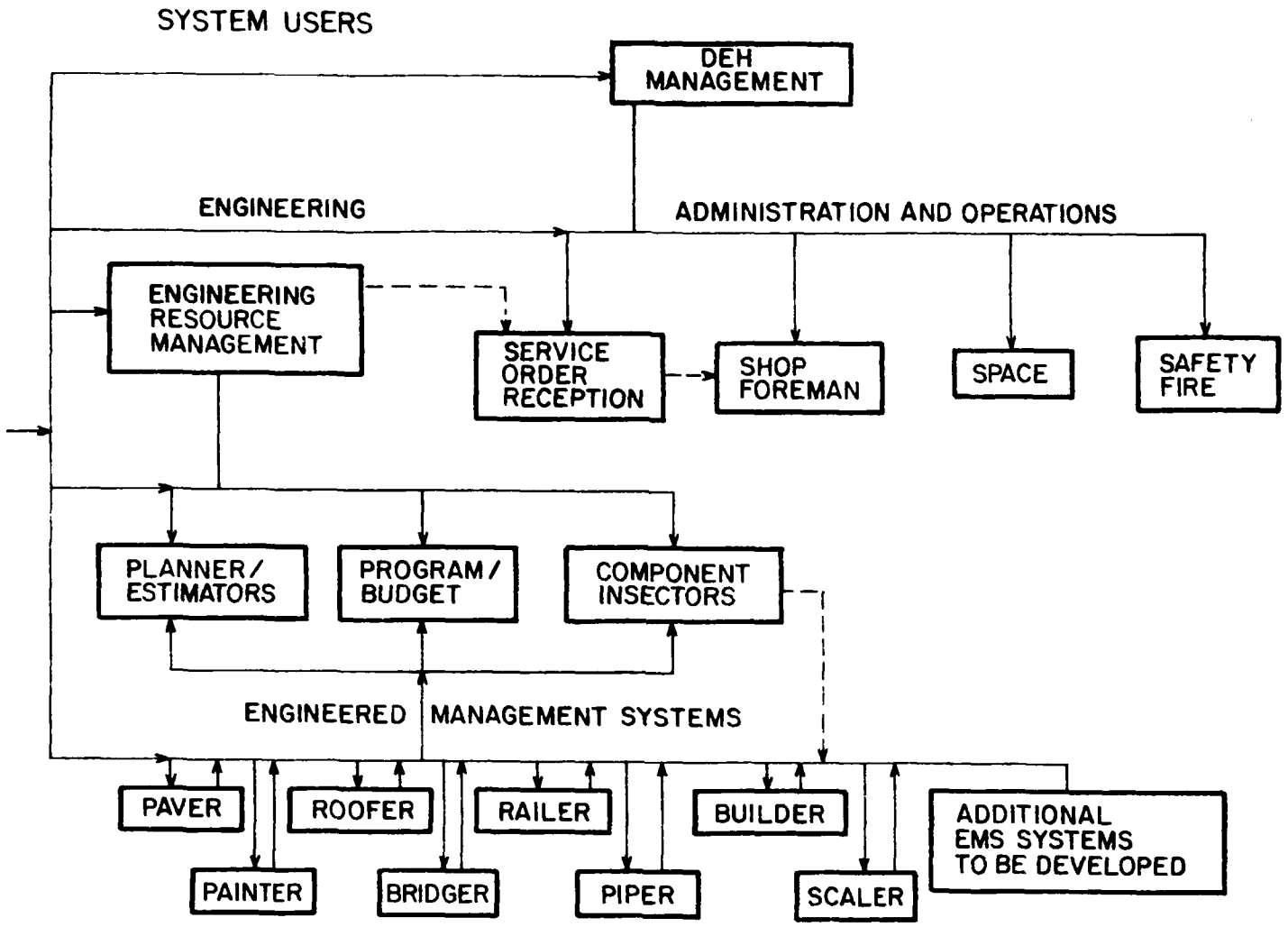

Figure 13. (Cont'd).

- Complete automated analysis on facilities such as calculations for material in sections of interest, area, and inventory.

- Display a geographic map of facilities and overlay infrared images of roofs, walls, pipelines, or other components for thermal anomaly analysis.

- Look at closeups of facility exteriors and evaluate the condition of facades, windows, doors, siding, and landscapes in detail.

- Compare visual and infrared images of facilities with line drawings to understand the nature and source of visually apparent defects or thermal anomalies.

- Compare specific floor plans and drawing details to site conditions.

- Locate problems identified in service orders for specific components (e. g., windows, doors, exterior air-conditioning units).

- Complete code compliance surveys for exterior elements to meet fire, safety, handicap access, and other requirements.

- Acquire a "feel" for how a facility really looks from the exterior (useful for space allocation, housing assignments, etc.).

- Complete inspection reports and scoping estimates at the workstation for M&R work.

- Use the automated processing features to expedite work. For example, reports developed at the workstation would be entered in the system electronically, allowing for immediate processing in other areas (e.g., accounting, manpower planning, BMAR totals).

- Apply image-processing capability to images being studied for maintenance evaluation. Areas could be calculated from the screen, and combing and separation techniques could be used to determine relative degrees of deterioration for components (e.g., painted surfaces). Other image processing functions could identify and count specific component types.

- Complete a detailed analysis of infrared images leading to automatic calculation of temperature gradients, areas of anomalies, and other diagnostic parameters.

- Reference infrared images to engineering drawings for more diagnostic evaluations.

- Have shop maintenance personnel look at a specific piece of equipment or component when a service call or work request is received. This step would allow them to identify parts and tools needed for the job before making the site service call.

- Have space planners view the information when allocating space for clients. In this way, the planner and client can take a look at the space without a site visit.

- Do detailed energy audits at the workstation.

Many of the capabilities cited above can be achieved using commercially available hardware/software systems. These systems can store and manage numerical facilities data, geographic data, and line drawing data. Systems available to meet the facilities data base requirements are summarized below. Several capabilities, particularly those related to automated analysis of images, represent extensions of the state of the art. The developmental effort required to implement these

capabilities in developing and managing the expanded IFS-M data base concept presented above is discussed in the final section of this chapter.

Existing Capabilities and Systems

Facilities Data

A wide variety of facilities management software packages is available commercially or from within the Army. These packages typically use relational data base techniques to manage numerical data for a group of facilities. The kind of information stored and managed in these systems deals with facility types, uses, areas, materials, equipment, inspection frequencies, and generalized condition codes. Economic data are linked to each of these information categories. Depending on the sophistication of the system, work order and maintenance requirements can also be integrated with the facilities inventory and accompanying information. PM scheduling can be incorporated into the system as well. Cost estimates can be generated for long- and short-range maintenance requirements that have been identified. The IFS-M system currently under development, as described earlier, is an example of a minicomputer-based, numerically oriented system. The EMS family represents microcomputer-based systems.

Geographic Data

Again, a large selection of geographic information system hardware and software packages is available commercially. The range is wide both in terms of sophistication and price. Simple packages are available that allow hardcopy maps to be digitized from a pad and stored on disk or tape with a limited amount of geographic information associated with the map (e.g., scale, coordinates, areas). Advanced packages are available that can use automated digitizing hardware, incorporate relational data base capability with the geographic data, permit image processing, and allow for video and photographic overlay and updating. Prices for systems range from $3000 to several hundred thousand dollars. The "baseline" geographic information requirement needed to support the proposed facilities data base includes the following key elements:

- The ability to display and print geographic maps of facilities in polygon, line, and point format in varied scales.

- A relational data base so that numerical information for a facility can be queried and/or displayed along with the mapped information being displayed (e.g., areas of a building or roof material types associated with a displayed facility).

- The ability to graphically "overlay" infrared information onto the vector-based facility map.

- A graphics capability that allows facilities to be "highlighted" visually on a map when they have certain characteristics of interest (e.g., highlight all facilities that have not had a component inspection in 1 year or longer).

Some installations already use geographic mapping systems such as GRASS that meet or exceed the above requirements. For these installations, it is proposed that the geographic information be stored on optical disk and software be developed to integrate this information with the numerical, line drawing, and visual information. For installations that do not have a computerized geographic information system, aerial video images can be used establish a geographic information system (GIS). Many technical approaches are possible when establishing a GIS, depending on the existing geographic

data base.[43] If fairly reliable hardcopy maps are available, the best approach is to have these digitized and use a video overlay system to update and ensure accuracy. If hardcopy maps are not in a format that can be readily digitized, it may be more practical to use a video approach in the initial aerial data collection. This procedure enables accurate mapping to be developed without a preexisting hardcopy map. The end result of each of these methods is a geographic information data base in digital form that can be stored on optical disk and integrated with the other information "components."

Line Drawing Data

Another key element of the proposed integrated facilities data base is the use of existing drawings where available. The most efficient and powerful means of using these drawing data is to digitize and store them on optical disk. Storage could be in the same central optical library described in the previous section. Software would manipulate the digital images of the line drawings in the same way as the visual images. The Army CAD Buy has been awarded to the Intergraph company. Research is ongoing at USACERL to explore this technology.

The digitization of drawings could be handled initially by a document scanner purchased by the installation or at a central location outside of the base. Drawing digitizers are available commercially in a wide range of types and prices.[44] For large installations, purchasing a document scanner to use in conjunction with an optical disk encoder would optimize efficiency and flexibility. Once the drawings are digitized, the same flexibility exists for their use as the other data discussed.

It should be pointed out that this initial data base of line drawings would essentially be "pictures" of actual hardcopy drawings. They could be modified using commercially available graphics packages that essentially act as electronic drafting boards. The initial drawing images and revisions would have no "intelligence." This means numerical data pertaining to line drawings could not be calculated electronically or keyed automatically to a relational data base. The advantage to having the line drawings on optical disk is the speed and efficiency with which the documents can be retrieved and viewed.

Scanning, digitizing and encoding existing drawings to optical disk as described above are proposed for cases where no previous CAD data base of drawings exists. For installations that have CAD data bases for some or all as-built drawings, it is proposed that these be integrated with the facilities data base. The existing CAD drawing data base would be encoded on optical disk. It is understood that the optical disk is currently a "write once, read many" storage medium. Revisions could, however, be encoded with the CAD software and applied upon recall of the original optical disk images. The associated numerical data base information generated by the CAD drawings could be stored on optical disk or left on tape, depending on the number of revisions anticipated and the CAD data base structure.

The integration of line drawing information into the facilities data base would provide several key functions. First, it allows speed and efficiency in accessing drawings. Second, it enables numerical data associated with the line drawings to be used for many applications. Third, it permits visual and infrared images stored in the data base to be compared and referenced to line drawings.

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[43] R. F. Austin, "Raster Systems in a Production Environment Reduce Labor Time and Costs," *Design Graphics World* (March 1985); D. J. Reuquet and O'Callaghan (Ed.) *Design Implementation of Computer-Based Geographical Systems* (IGU Commission on Geographical Data Sensing and Processing, 1983).

[44] R. F. Austin; M. S. Monmonier, *Computer-Assisted Cartography: Principles a[illegible]rospects* (Prentice-Hall, 1982).

Developmental Requirements for the Automated Imaging System

As described in the preceding section, the basic technologies required to implement the proposed automated imaging system already exist. However, supporting the specific system as described will require the available technology to be modified. These requirements are best understood in terms of hardware and software components.

Hardware

1. Video Camera/Infrared Scanner. Developmental requirements for this equipment involve coupling an infrared scanner with a video camera and providing synchronized output on a portable VCR tape. The camera/scanner would have to employ a single viewfinder and have both the camera and scanner focus on the same point. Preliminary discussions with infrared scanner manufacturers indicate that the concept is entirely feasible. Utility companies have developed similar "home grown" systems for their own use. The major technical issues involved are potential parallax problems in making the scanner and camera focus on the same point.

2. Optical Video Laser Disk Encoder. Two different types of technologies have been discussed with reference to optical disk encoding. One approach involves acquiring visual data on video cassette tape and sending the tapes to a commercial laboratory where the data would be encoded on optical disk. The 3M Corporation is the primary supplier for this kind of optical disk encoding. Its method stores an analog representation of the image on the disk, with the potential to store digital code on an accompanying audio channel on the disk. This process allows images to be filed and referenced digitally, with the actual image representation remaining in analog form. An advantage of this approach is high color resolution. A disadvantage is that images are not digitized for storage, meaning that if image processing is to be done, images must be "grabbed," digitized, and stored in digital format prior to processing. The other drawback to this system is that the authors are not aware of a commercially available system capable of producing such optical disks in a "stand-alone" environment. 3M currently produces its disks in an industrial laboratory and does not sell the technology itself. As a result, producing a single disk original is expensive ($3600). The development of an optical disk-encoding device capable of taking color video cassette images and encoding them on optical disk in a minicomputer environment at an Army installation would be one way to overcome this drawback. The price of such a system would have to be in the range of $100,000 to $200,000 per unit to be cost-effective. This encoding equipment could be installed on several Army optical encoding centers around the country or perhaps obtained through a commercial vendor on a licensing basis.

The second encoding method is a stand-alone system that enables documents to be scanned, digitized, and encoded on optical disk. This is the type of system sold by FileNet as described earlier. Currently, FileNet's system is designed for office-sized documents and cannot scan and digitize architectural drawings. To the authors' knowledge, there is currently no specific system available for digitizing videotape input and encoding it on optical disk. An upgraded FileNet type of system with the ability to digitize video, line drawing, and document input and encode it on optical disk would appear to provide the optimal solution at this point. The capabilities described all currently exist, but have yet to be integrated into a single system.

Software

1. Integration of Data Base Components. The proposed system will require software that allows numerical geographical, architectural and image data bases to be used together. The software for each separate system is well developed. No software, however, is designed to be used in an integrated fashion for facilities management and condition assessment. Software must be developed to produce a well integrated system capable of using the information in the data base to the maximum potential. For applications involving an installation-level IFS-M minicomputer environment with component-

specific EMSs resident in the system, the issue is to enable a relational data base management program such as Oracle to integrate the visual components of the data base with the numerical, geographical, and line drawing components.

Developing a workable file structure and image library management software is a formidable challenge. For applications where an integrated facilities data base is not envisioned, software must be developed to enable component-specific EMSs to relate to relevant visual images. This development will involve integrating existing EMS data base management software with an image file structure and image server hardware. This feature would range from the optical disk "juke box" for large applications to a single optical disk player for small applications.

2. Specific Image-Processing Tools. Automating the extraction of numerical and qualitative information from optical (and infrared) images requires image processing and pattern recognition. This technology, as applied to component inspection and facilities inventory, is still in its infancy. Numerous technological developments have occurred in related applications such as automated inspection in manufacturing and medical imaging. These technologies, however, require adaption in order to apply to the domain of constructed facilities. An effort is currently underway, for example, to automate the inspection of pavement surfaces. Many other inspection and inventory applications for constructed facilities await development. Therefore, image processing and pattern recognition applied to facilities inventory and component inspection constitute a significant research and development area supporting the automated imaging concept.

7 CONCLUSIONS AND RECOMMENDATIONS

The original intent of this study was to evaluate and recommend component inspection technologies that would support Army facilities maintenance. To develop an understanding of the need for these technologies, Army facilities personnel were surveyed. These contacts revealed that improvements in component inspection technology alone will not greatly improve facilities maintenance activities. Feedback indicated that: component inspections have little perceived value when the maintenance budget is inadequate for very obvious problems; component inspection data are unused for lack of an organized process that exploits the data in making plans and decisions; and planning, prioritizing, and optimizing the allocation of maintenance resources are really the main issue and need. These findings suggested that the study take a broader perspective. As a result, the original scope was expanded to evaluate and recommend technologies that would improve the process of allocating maintenance resources.

Informational needs were studied at three levels: installation, facility, and component. It was concluded that, in addition to needing component and facility condition data, management and staff lack accurate, up-to-date accessible information on facility and component inventories to manage an M&R program efficiently and effectively. Where this information exists, it is not easily accessible or transferable to any kind of data base or facilities management system. Therefore, technology that can rapidly capture condition and inventory data, and efficiently transfer those data to a data base, would be the best solution. Several available technologies were reviewed. Although many technologies have been developed to address specific facility components (e.g., radar for detecting pipe leaks), one generic technology has emerged which satisfies several needs in both the inventory and inspection domains--automated imaging.

An automated imaging concept has been developed to include both optical and infrared imaging. Optical images contain inventory information (areas, locations, quantities) and inspection information (cracks, stains, deformations). Infrared images provide subsurface and nonvisual condition information, such as that related to the presence of moisture, cracking, and other types of deterioration. The concept combines image capture of aerial, ground-based, and interior levels, and automated image transfer to optical disks. This concept for rapid data capture and transfer would go hand-in-hand with a facilities data base management system such as that being developed under IFS-M and the various EMS.

A detailed approach for implementing the automated imaging concept has been proposed and initial work is in progress at USACERL. The approach recommends the expansion of the IFS-M/EMS data bases concept to incorporate geographical, architectural line drawing, and visual and infrared image data. Much of the technology required for the development of this automated imaging approach is now available off-the-shelf. Some of these technologies, such as hardware for data transfer from videotape to optical disk and application-specific image-processing software, require further development.

It is clear that management of an infrastructure facility system such as that found at an Army installation requires large quantities of supporting information that must be readily accessible to many individuals for a variety of purposes. This need can only be addressed through some coordinated data base management system implemented at the installation level. The current development of IFS-M provides a framework for such a system. The parallel development of the EMSs will provide application-specific management tools that can both exploit and augment this data base.

The initial and recurring costs outlined in Chapter 6 are based on those expected for an average installation. Actual costs would be expected to vary based on the installation's land area as well as the number of its facilities. In addition, as concluded above, if the resources needed to implement and operate such a video system were instead invested in additional manpower to perform inspections, many of the facilities management problems described earlier in this report would still not be rectified.

While in some cases the lack of resources has prevented the establishment of an effective program, the information must still be made available in a format that is easy to retrieve and use. Just hiring more inspectors will not make that happen.

Improved management of Army facilities requires technology that will help optimize allocation of finite maintenance resources. This conclusion, and the issues underlying it, have been supported by a Presidential commission investigating public infrastructure systems.[45] The development and integration of automated imaging systems could potentially fill this technology gap.

Many existing technologies for component inspection were outlined in Chapter 4 of this report. Most of these are proven and work very well for the described application. It is recommended that these current technologies be used until the video imaging concepts can be fully developed and implemented. Even then, many of these technologies will remain valid.

It is recommended that the Army continue to pursue research and development of such integrated systems through USAEHSC and MACOM sponsorship. Development of the data base management system, EMSs, and the data capture/transfer technology will involve a substantial effort. In addition, considerable investment of operational resources will be required to adapt these technologies and implement them in the field. It is critical that Army facilities personnel "buy into" the new technology. This acceptance may be difficult to achieve in environments where the obvious maintenance needs are underbudgeted and longer range developments are tabled in the interest of more pressing immediate needs. It is clear, however, that investment in the technology alone will not guarantee a successful product in the future; there must be an accompanying acceptance and commitment by the potential users.

Development of prototypes to demonstrate the aerial, ground-level, and interior imaging concepts should be pursued. Such prototypes will serve to further explore the concepts technically through the analysis and testing procedures. Technical issues that need to be studied further through prototyping include the establishment of a proper balance of height, width, and camera resolution for practical and economical application.

Once prototypes are developed, the technologies can be demonstrated. From those demonstrations a complete analysis of costs and benefits can be undertaken. It would also serve to determine if the video imaging technologies would work as the concept proposes. The integration of the prototypes into IFS-M/EMS has great potential.

METRIC CONVERSION FACTORS

1 ft = 0.305 m
1 yd = 0.836 m
1 mi = 1.61 km
1 sq ft = 0.092 m^2

[45] National Council on Public Works Improvement, *Fragile Foundations - A Report on America's Public Works* (February 1988).

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APPENDIX A:

PERSONAL INTERVIEWS

Department of Defense Personnel

Site Visits

The following Fort Devens, MA, DEH staff were interviewed during a meeting held in conjunction with a site visit and tour of the facilities:

LTC Mark Malkasian	Director, DEH
Joseph Tammaro	Deputy Director, DEH
Ron Ostrowski	DEH-ERMSSD
James C. Chambers	DEH-MESB
Laurie Suamala	DEH-Chief, Housing Division
Harold Bradbury	DEH-Building and Grounds
Robert Orr	DEH-Utilities Division
Rosanne Lato	DEH-MESB
Tim Resendes	DEH-HSG
Jon Grafton	DEH-HSG

At Fort Ord, CA, a site visit and tour of the facilities were conducted along with interviews with the following DEH staff:

Ed Kanciruk	MESB-Director
Bob Sharp	MESB-Industrial Eng. Services
Sylvia Nasri	DEH-Director, Work Management Branch

U.S. Army Engineer, Capital Area (ECA) DEH staff were interviewed in conjunction with site visits to Fort Myer, DC, and Cameron Station, VA. Interviewed were:

Rich Rice (Fort Myer)	Director, Operations & Maintenance Area
Ray Crouch (Fort Myer)	Structural Component Inspector
Skip Fitzgerald (Fort Myer)	Electrical Component Inspector
John Maurer (Fort Myer)	Mechanical Component Inspector

Ray James (Cameron Station)	Air-Conditioning Shop Foreman
Mr. Mullins (Cameron Station)	Plumbing Shop Foreman

At the U.S. Army Engineering and Housing Support Center (USAEHSC), Leo Oswalt, IFS-M, Fort Belvoir, VA, was interviewed. He is Project Coordinator for the IFS-M concept and hardware specifications.

Telephone Interviews

The following individuals provided information by telephone. The objective of the interviews was to determine current maintenance inspection practices.

Don Benson	Facilities Branch Chief, Tooele Army Depot, UT
Tommy Houston	Chief, Engineering Resource and Management Division, Fort Stewart, GA
Rusty Wilkerson	Deputy Director, DEH, Fort Campbell, KY
Ken Paton	Fort Devens, MA
Lloyd Frentzen	USACE, Sacramento District, CA
Paul Styer	USAEHSC, Fort Belvoir, VA
Al Knehans	USAEHSC, Fort Belvoir, VA
Tim Flarety	Fort Ord, CA
Joe Glen	USACE, Tulsa District, OK
Steve Chapman	USACE, Tulsa District, OK
Greg Forrest	Fort Dix, NJ
Harold Juhola	Great Lakes Navy Public Works Center

Private Sector

Anthony Braccia	Braccia and Assoc., San Francisco, CA
Eugene Simko	Daverman Assoc., Tucson, AZ
Ron Passaro	Resi-tech, Redding, CA

MIT Physical Plant Staff

David Millay	Mechanical Division
Warren Scott	Mechanical Operations, A/C, Refrigeration Boilers
Michael Taub	Central Utilities Division
Jake Kredi	Electrical Division

APPENDIX B:

FORMAL SURVEY RESULTS

Written Survey

Compiled below are the results of a written survey issued from the Office of the Assistant Chief of Engineers (OACE), DAEN-ZCF-B, to all MACOMs. The survey was then redistributed to all MACOM installations. Those installations which responded are listed below. The results of the survey are then presented for the Army as a whole and then by MACOM (FORSCOM, TRADOC, AMC, USAREUR, Japan/Korea, and Other). The results for the smaller MACOM are consolidated to ensure anonymity. The frequency represents the number of responses and the percentage represents the frequency divided by the total number of responses (109).

MACOM Respondents

FORSCOM

Fort Campbell, KY
Fort Devens, MA
Fort Hood, TX
Fort Sam Houston, TX
Fort Lewis, WA
Fort McCoy, WI
Fort McPherson, GA
Fort George G. Meade, MD
Fort Sheridan, IL
Fort Stewart, GA
Fort Irwin, CA
Fort Ord, CA
Fort Pickett, VA
Fort Bragg, NC

TRADOC

Fort Belvoir, VA
Fort Bliss, TX
Fort Chaffee, AR
Fort Dix, NJ
Fort Eustis, VA
Fort Gordon, GA
Fort Benjamin Harrison, PA
Fort Jackson, SC
Fort Knox, KY
Fort Leavenworth, KS
Fort Lee, VA
Fort McClellan, AL
Fort Rucker, AL
Fort Leonard Wood, MO
Fort Sill, OK
Carlisle Barracks, PA
Fort Benning, GA
Fort Richardson, AK

AMC

Depot Systems Command
- Anniston AD, AL
- Lexington-Blue Grass AD, KY
- Red River AD, TX
- Savanna AD, IL
- Sharpe AD, CA
- Sierra AD, CA
- Tobyhanna AD, PA
- Toocle AD, UT
- Corpus Christi AD, TX
- Navajo Depot Activity, AZ

Laboratories Command
- Harry Diamond Laboratory, MD
- Material Technical Laboratory, MA

Government-Owned, Government-Operated (GOGO) Facilities
- Picatinny Arsenal, NJ
- Pine Bluff Arsenal, AR
- Rock Island Arsenal, IL
- Rocky Mountain Arsenal, CO
- McAlester AAP, OK

Missile Command
- Redstone Arsenal, AL

Aviation Systems Command
- St. Louis Area Support Center, IL
- Natick Research, Dvmt & Eng Cntr, MA

Test & Evaluation Command
- Dugway Proving Ground, UT
- Aberdeen Proving Ground, MD
- White Sands Missile Range, NM
- Yuma Proving Ground, AZ
- Jefferson Proving Ground, IN

USAREUR

V Corps, Frankfurt, West Germany
- Dir, Engineering and Housing
- USMCA, Bad Kreuznach
- USMCA, Baumholder
- USMCA, Frankfurt
- USMCA, Giessen
- USMCA, Hanau

VII Corps Stuttgart, West Germany
USMCA, Aschaffenburg
USMCA, Augsburg
USMCA, Bad Toelz
USMCA, Garmisch
USMCA, Garmisch - Berchtesgaden
USMCA, Goeppingen
USMCA, Heilbronn
USMCA, Munich
USMCA, Neu Ulm
USMCA, Neumberg
USMCA, Schweinfurt
USMCA, Stuttgart
USMCA, Wuerzburg

21st Support Command, Kaiserslautern, West Germany
47th Area Sup Gp, Burtonwood, England
NATO/SHAPE
USMCA, Kaiserslautern
USMCA, Mannheim
USMCA, Pirmasens
USMCA, Karlsruhe
Reichel Kaserne, Reinberg
USMC, The Netherlands
29th Area Support Group
USMCA Worms
USMCA Zweibruecken

Southern European Task Force, Vicenza, Italy
8th Support Group (Camp Darby)
USMCA, Vicenza

7th Army Training Command, Grafenwöhr, West Germany
USMCA, Grafenwöhr

<u>Japan/Korea</u>

US Army Japan, Honshu
Honshu
Okinawa

Eighth US Army, Seoul, Korea
2nd Infantry Div
Camp Humphreys (DEH)
Camp Page (DEH)
Combined Field Army (DFE)
Pusan (DEH)
Taegu (DEH)
Western Corridor (DFE)

Other

Arlington Hall Station, VA
Fort Detrick, MD
Walter Reed Army Medical Center, DC
Bayonne Military Ocean Terminal, NJ
Oakland Army Base, CA
Sunny Point Military Ocean Terminal, NC
US Military Academy, NY
US Army Southern Command, Panama
USAISC - Fort Ritchie, MD
US Army Engineer Activity, Capital Area, Fort Meyer, Arlington, VA

Department of the Army (Total)

1. What facility component inspections do you do?

	Answer	Frequency	Percentage
-	No inspection	20	18.3
-	Structures & roofs	58	53.2
-	Roads & bridges	27	24.8
-	Utilities	24	22.0
-	Equipment (mech, elec.)	31	28.4
-	All components (no detail given)	23	21.1

2. Who does the component inspections?

	Answer	Frequency	Percentage
a.	Full-time inspectors:	44	40.4
	Breakdown:		
	1 or 2	24	22.0
	3 to 5	13	11.9
	> 5	7	6.4
	Man-years devoted to inspection (41 sites):		
	< 1	8	7.3
	1 to 2	20	18.3
	> 2	14	12.8

b. Part-time inspectors:	50	45.9
Breakdown:		
1 or 2	16	14.7
3 to 5	16	14.7
> 5	18	16.5
Man-years devoted to inspection (51 sites):		
< 1	18	16.5
1 to 2	20	18.3
> 2	6	5.5
c. Inspection by contract:	29	26.6
Breakdown:		
< $10,000/yr	6	5.5
$10,000 to $100,000/yr	19	17.4
> $100,000/yr	4	3.7
d. Inspection by troop labor:	4	3.7

3. How are inspections carried out?

Question	Frequency of "yes"	Percentage
a. Do you have a scheduled inspection program in place?	60	55.0
b. Is IFS used to schedule inspections and to accumulate results?	33	30.3
c. Is 100% component inspection being used?	51	46.8
d. Do you have fixed inspection frequency?	52	47.7
e. Have you used nonvisual inspection techniques?	38	34.9

4. How do you use the inspection information?

Question	Frequency of "yes"	Percentage
a. Determine immediate M&R requirements	82	75.2
b. Establish work priorities	66	60.6
c. Prepare project approval documentation	60	55.0
d. Scope & specify M&R projects	63	57.8
e. Determine URR	56	51.4
f. Prepare annual work plan	62	56.9
g. Prepare long-range M&R work plan	61	56.0
h. Determine backlog of M&R (B[illegible]R)	58	53.2

5. Inspection technologies used:

Technology	Frequency	Percentage
a. Infrared scanning	23	21.1
b. Video scanning	18	16.5
c. Others		
1) Industrial Stethoscope	1	0.9
2) Ultrasonic	3	2.7
3) Electrical Metering	3	2.7
4) Eddy Current	1	0.9
5) Nuclear Moisture	1	0.9
6) Sound Levelmeter	1	0.9
7) Other (not described)	2	1.8

Major Commands (MACOMS)

Question	FORS-COM	TRA-DOC	AMC	USA-REUR	Japan/ Korea	Other
Total number of respondents	15	17	25	33	9	10
1. What facility component inspection do you do?						
- No inspection	2	3	2	11	0	2
- Structures and roofs	10	10	16	12	4	6
- Roads and bridges	5	2	10	2	3	5
- Utilities	2	5	9	2	3	3
- Equipment (mech., elec.)	4	6	10	2	4	5
- All components (no detail given)	2	3	4	8	5	1
2. Who does the component inspections?						
a. Full-tim inspectors:						
Breakdown:						
1 or 2	2	4	5	8	4	1
3 to 5	1	4	0	4	2	2
>5	3	0	1	1	1	1
Man-years devoted to inspection (41 sites):						
<1	1	1	1	2	1	2
1 to 2	2	3	4	5	3	3
>2	3	3	0	5	2	1

Question	FORS-COM	TRA-DOC	AMC	USA-REUR	Japan/Korea	Other
b. Part-time inspectors:						
Breakdown:						
1 or 2	1	3	7	5	0	0
3 to 5	4	2	4	4	1	1
>5	2	4	7	4	0	1
Man-years devoted to inspection (51 sites):						
<1	1	3	9	3	1	1
1 to 2	3	4	4	8	0	1
>2	2	1	3	0	0	0
c. Inspection by contract:						
Breakdown:						
< $10,000/yr	0	0	2	2	0	2
$10,000 to $100,000/yr	2	3	11	2	0	1
> $100,000/yr	1	0	1	1	0	1
d. Inspection by troop labor:	2	0	1	0	0	1
3. How are inspection carried out?						
a. Do you have a scheduled inspection program in place?	8	9	16	14	7	6
b. Is IFS used to schedule inspections and to accumulate results?	5	6	2	8	8	4
c. Is 100% component inspection being used?	7	10	9	11	9	5
d. Do you have a fixed inspection frequency?	9	8	7	14	9	5
e. Have you used nonvisual inspection techniques?	4	5	12	7	2	8
4. How do you use the inspection information?						
a. Determine immediate M&R requirements?	11	13	22	19	9	8
b. Establish work priorities?	8	13	19	12	6	8

Question	FORS-COM	TRA-DOC	AMC	USA-REUR	Japan/ Korea	Other
c. Prepare project approval documentation?	8	10	16	10	8	8
d. Scope & specify M&R projects?	11	3	19	14	8	8
e. Determine URR	5	10	16	9	9	7
f. Prepare annual work plans?	5	13	18	10	9	7
g. Prepare long-range work plans?	5	12	19	9	9	7
h. Determine backlog of M&R (BMAR)?	6	12	19	10	8	3
5. Inspection technologies used:						
a. Infrared scanning	2	6	7	4	0	4
b. Video scanning	3	3	7	4	0	1
c. Others	1	0	4	2	2	3

Statistical Analysis of Survey Responses

Background

Of the 109 responses, 82 were used in the analysis described below. The remaining 27 were either incomplete or lacked supporting documentation in the "redbook."[46] The following quantities (per installation per year) were considered in the analysis.

1. Inspection Expenditures ($): These were computed from the questionnaire responses, by assuming $50,000/manyear, and adding internal to contracted inspection expenditures.

2. Total DEH Budget ($): This was obtained from the redbook and combines maintenance, operations, and minor construction.

3. Maintenance Budget ($): Also obtained from the redbook.

4. Total Area of Enclosed Space (sq ft): Obtained from the redbook and used as a replacement for the total value of the capital plant.

[46] *Facilities Engineering and Housing Annual Summary of Operations Report* (FY86).

Analytical Results

The statistical analysis revealed some interesting information:

1. The maintenance expenditures tend to represent a fixed proportion of the total budget for most bases. A correlation coefficient (R^2) of 0.945 between maintenance ($) and total budget ($) was found.

2. There is practically no relationship between inspection ($) and maintenance ($) (R^2 = 0.04) or between inspection ($) and total budget ($) (R^2 = 0.13).

3. The square footage of enclosed space has a large influence on the amount of maintenance (R^2 = 0.86).

4. There is no correlation between the area of enclosed space and the inspection amount (R^2 = 0.03).

These results suggest that maintenance is a fixed percentage of total budget, and that much of it is programmed independently of information from inspections. Inspections themselves are not programmed in proportion to total maintenance volume.

Follow-on Telephone Survey

Background

When compiling the written survey results, it was found that follow-up discussions were useful for ensuring an understanding of the questions and interpretation of the results. Accordingly, several installations were queried.

Discussion

It was clear that most installations desire to have a more aggressive inspection program because the information obtained would serve several useful purposes, but that manpower or money constraints are preventing such a program. Generally, they are attempting to do the best they can with their limited resources. In most cases, inspection of locally determined "critical" components has high priority. Inspection technologies that can gather the necessary information with fewer manpower requirements would be generally accepted.

APPENDIX C:

DISCUSSION OF TERMINOLOGY USED IN TABLE 1

Installation Level

Decision Types

1. Inspection Programming and Resource Allocation: involves decisions about the type and frequency of inspections to be performed on a facility, the amount of money to be allocated for inspections, and the staffing required. Equipment budgets and allocations for inspections are also decided at this level. In addition, facilities to be inspected are identified and facility inspection priorities are established.

2. Maintenance Decisions: involves decisions on the structure and allocation of the maintenance budget. Decisions on the maintenance investments required to maintain the level of installation readiness desired are made at this level. Facilities that must be repaired or replaced to ensure safety and code compliance are also identified. In addition, facilities or components that should be replaced because their maintenance costs exceed replacement costs or they no longer function effectively are identified. Areas where maintenance expenditures can be reduced by more preventive maintenance or by improving inspections are established. The results of these decisions are prioritized to ensure maximum efficiency.

3. Maintenance Budget: refers to establishing the total resources required to maintain the installation at a specified performance standard. Ideally, the budget is based on the actual condition of the entire facilities inventory and the facilities' requirements.

Information Requirements

1. Inventory Data: a complete record of all facilities on an installation in terms of function, size, and composition. This includes using line drawings of the installation that illustrate the spatial relationships between facilities, sizes, identifications, and uses.

2. Performance Data and Impact of Maintenance on Performance: a standard of performance developed from objective criteria for a particular facility. Actual condition and performance must be measured and evaluated in terms of standard and measurable quantities (e.g., as in PAVER, where a required standard condition of pavement for an installation can be established such as a PCI = 85 with the road network as a whole and the various pavement sections evaluated in terms of this standard). The relationships between maintenance and performance must also be characterized in usable form to support decision-making.

3. Impact of Facility Performance on Function of Installation: performance of individual facilities and groups of facilities must be measured in terms of their impact on the mission of the installation as a whole. Minimum performance levels below which a mission is seriously impaired must be defined. Investment in facility performance must be prioritized in this context.

4. Cost of Maintenance: needed to establish budgets and prioritize work when funding is constrained.

Approach

1. Automation to Aid in Data Acquisition: refers to automating the capture of facilities inventory and inspection information. An automated approach is also taken for converting raw inventory and inspection data into a form useful for integration into a facilities management system. The automation could be achieved using a combination of remote sensing and imaging technologies for data capture (e.g., video cameras, infrared scanners) with data conversion and storage devices (video recorders, optical video disk encoders and players) to automate the data entry into the system. The objective is to enable inventory and inspection information to be rapidly and efficiently captured, entered, and integrated into a facilities management system.

2. Data Base Management: refers to the maintenance and use of actual facility performance and inspection data for the facilities on an installation. Three key concepts are involved: (1) the initialization and maintenance of a facility inventory; (2) the association of condition and performance data into this inventory; and (3) the ability to manipulate, sort, and interpret the data in meaningful ways.

3. Resource Allocation: prioritization of maintenance resource usage based on the knowledge of required performance levels for facilities and the impact of individual facility performance on the installation as a whole. Maintenance requirements related to differing performance levels must also be defined.

4. Optimize Life-Cycle Cost: maintaining installation performance at a prescribed level while minimizing the cost of operation and maintenance.

Technology

1. Remote Sensing, Automated Imaging, Image Processing, and Automated Data Entry: initialization of the facilities inventory in the data base can be aided by the use of groundborne and airborne video cameras and infrared scanners. The application envisioned at the installation level involves video and infrared images of above-ground facilities captured from an aircraft. This would enable rapid capture of installation-level inventory and inspection information. The scale of these aerial images (approx. 1 in. = 50 ft) would allow items such as facility sizes and spatial relationships, dimensions to an accuracy of fractions of feet, material types, number of components, and some component distress types (water penetration on built-up roofs, thermal anomalies on pavements) to be extracted from the images using image-processing techniques. Data entry into a facilities data base is automated using data acquisition technologies to digitize and store the visual information as a component of the data base.

The video and infrared imaging technologies required for the automated imaging system described are well developed and available commercially. Aerial infrared imaging technology is currently used by USAEHSC to conduct roof condition surveys. Aerial video techniques are also employed as data collection tools for commercially available geographic information systems. The Hunter GIS is an example. Electronically shuttered video cameras suitable for the application described also are commercially available. The Panasonic D 5000 is an example. Data aquisition devices are available which transform analog video cassette tape input into digital form capable of storage in a computer. This digitizing equipment is available for mini- and microcomputer applications. Optical disks, players, and encoding devices are also currently available to enable efficient storage and access of visual information in a computer data base. What is not currently available is an integrated system that employs these technologies to support a visual component of a facilities data base.

2. Data Base Management Systems and Geographic Information Systems: refer to computer software that structures a data base of maintenance information to be used to improve maintenance

management and decision-making. EMS and IFS-M are efforts in this direction. A wide range of commercially available software packages allows relational data bases to be developed in support of maintenance and inspection functions. The Oracle software being used for IFS-M is an example of a minicomputer package. R:BASE and DBase data base management systems are examples of microcomputer-based packages used in developing EMSs. Geographic information systems also employ relational data base management concepts. All information in the data base is "keyed" to a geographic location, from which it can be referenced. The geographic information system developed for the Rock Island Arsenal is an example of such a relational geographic data base.

At the installation level, the information managed concerns broad maintenance issues across the installation and aggregated information developed from the more detailed data contained at the facilities level. Examples of the kind of information managed at this level are: how many separate administration buildings are on the installation, how many square feet of built-up roofing they contain, how many service calls were made on these roofs, when each roof was last inspected, and how it was inspected.

3. Expert Systems: computer software providing automated decision support, assisting in the identification and prioritization of maintenance needs. An example would be a software package with the following inputs and outputs. Assume input requirements of the installation's mission, facility inventory, maintenance budget, and a condition rating of each facility. A possible output would be a specific installation maintenance strategy based on identification of the five most critical facility types. Another possible output would be the identification of facilities for which the most cost-effective option over the next year would be replacement rather than continuing maintenance. Expert systems related to inspection and maintenance management are in their infancy and not well developed commercially.

Facility Level

Decision Types

1. Inspection Methodology: defines the methodology, frequency, costs, and technology required to assess the condition of a facility (individual or group). An example is a water distribution system. It requires an inspection methodology that begins with meter surveys and break history analysis, and progresses in detail to noise correlation and local geophone measurement. Facilities such as barracks would have a collective methodology, as well as an individual building methodology which would be the same for all barracks buildings.

2. Maintenance Specification: defines the work required to bring the facility up to an acceptable operating standard and maintain it at that standard. An example is draft Technical Manual (TM) 5-628.[47]

3. Repair/Replace/No Action Decision: Is it more cost-effective to repair a defective facility, replace it, or defer action to some later time?

Information Requirements

1. Inventory and Inspection of Facilities To Determine Condition and Performance: a complete inventory and record of the condition of all facility types and facilities is needed. For example, the physical plant of an installation must be categorized by facility type (i.e., roads, water distribution system, buildings). Individual facilities within the facility type must be identified (e.g., Troop Barracks

[47] TM 5-628, *Railroad Track Standards*, Draft (HQDA, March 1988).

Bldg. 101 is a facility within the facility type "buildings"). An inventory that identifies types and number of components within a facility must also be maintained. An objective condition and performance rating for each facility must be maintained based on the actual physical condition of its component parts (e.g., as in RAILER where the overall track structure condition index (TSCI) is derived from the condition indexes of the rail and joints, ties, ballast and subgrade, and turnout components). Line drawings show in pictorial form the size, layout, etc., of each facility.

2. Condition/Performance Assessment: evaluation of the actual condition and performance of facilities (individual and by facility type) compared with requirements set at the installation level.

3. Impact of Maintenance on Past and Future Performance: relationship between actual maintenance performed and its cost compared to performance must be documented (e.g., is increased scheduled maintenance leading to fewer service calls, or, for another case, is maintenance at a certain level of effort [time/cost] supporting a defined performance level).

4. Maintenance Cost: maintenance expenditures must be predictable, quantifiable, and historically available for individual facilities and for facility types.

5. Maintenance Needs: work needs must be identified so that maintenance plans can be developed.

Approach

1. Automation To Aid in Data Acquisition: emphasis is again on the use of automated imaging techniques to enable the rapid, accurate acquisition of large amounts of visual data for storage in the data base. Automated imaging and data conversion are proposed as tools enabling facility, component inspectors or facilities management consultants to complete facility inventories and inspections more efficiently and use the results more effectively. Labor-intensive inventory initialization requirements at this level, inspector site visits to each facility, and reports documenting results can be reduced through automated imaging.

2. Data Access and Data Base Management: the data base viewed from the facility level is composed of both facility and component inventory and performance information. The facility is viewed both as a unique entity and as the sum of its components. This latter view requires each component to be inventoried and its condition assessed. Facilities are also grouped by facility type.

3. Automated Data Transfer: refers to technology that can translate plans and drawings to live digital records. These records can become part of the active inventory data base, which can be readily accessed and updated as required.

4. Programmed Inspections: each component in the facility should be inspected according to an inspection program defined by facility type and age, component type and age, facility usage, environmental exposure, and previous condition information. The program also identifies the level of detail for the inspection, ranging from determination of a simple condition index (network-level) to detailed description of distress manifestations and possible causes (project-level). This output requires that a specification of the inspection technology be used. (Note: network and project levels are defined in the text.)

5. Decision Models and Life-Cycle Cost Analysis: such models, addressing alternative maintenance strategies, should incorporate projected expense over the life-cycle of the facility. The impact of inspection information on optimality of such decisions should also be incorporated into these models.

Technology

1. Remote Sensing of Inventory and Condition: the imaging technologies employed for facility-level data acquisition are the same as those used at the installation level (video camera, infrared scanner, video cassette recorders). The imaging could be done from the ground level, from a vehicle, or on foot, providing an image with a scale on the order of 1 in. = 5 ft. This level of detail enables the extraction of information such as component dimensions, materials, and condition. The video and infrared images are recorded on cassette tape and are digitized and stored in the facilities data base. The images are "keyed" in the relational data base to the facility they represent. Data conversion and storage employ the same technologies as at the installation level. The basic technologies required to implement such a system exist. However, they have not been developed into an integrated system. Considerable further development is needed to automate the entry of facility data into the data base. Facility inspection applications for image processing software also require further development.

2. CAD: software used to generate graphic representations of data stored in the inspection and condition data base. A wide variety of CAD packages is available for both mini- and microcomputer environments. Currently, however, they are typically not capable of easy integration into a relational data base environment with geographic and visual information.

3. Data Base Management Software (DBMS): the facilities level would use the same relational data base management software as described for the installation level. The facilities level would contain much more detailed records for individual facilities. Information keyed to facilities at this level would include, for example, the inventory of mechanical equipment contained in a facility, estimated replacement value, age, inspection frequency, and an assessment of condition. Each facility might have 1000 or more pieces of information associated with it. The ground-based images contained in the data base would be referenced to individual facilities by relational data base management software at this level. The development of a data base file structure relating facility types, their components, and the visual images representing them requires an extensive effort. Office automation systems are available that employ similar technologies and file structures, but applications to facility inspections have not been developed.

4. "Electronic Clipboard": bar codes defining building components and optical scanners to enable quick, accurate inventory of components, assessment of their condition and any corrective action required on them. Using the optical scanner, bar code information of components would be electronically logged into a portable computer, which would be downloaded to a computer containing the facilities data base. Information defined by the bar codes would spell out space, material, and equipment types and basic condition ratings (i.e., good, fair, needs repair). This type of technology is expected to be used during facilities inventories and condition evaluations, where a detailed walk-through and visual inspection of all facilities are required. This is an established methodology used by facilities management consultants now.

5. Optical Scanners and Bar Codes: all facilities and components could be bar-coded. Inventory and inspection activities could use optical scanners to automatically obtain and enter the bar-coded data into the appropriate data base, along with other data collected in the field.

6. Inventory Sensing Devices: for example, sonic dimensional measurement device used to determine area measurements (for acquiring inventory data). These devices are commercially available from several sources (e.g., the Rangescanner by Exergen Corp.).

7. Expert Systems: computer software for automating interpretation of the sensor data. Very few are currently available relating to facility inspection.

8. Voice Systems: a system for translating human voice patterns into a data base. This system speeds the visual inspection process by eliminating the need to record information manually. The Voice-Operated Inspection System--VOIS®--is commercially available from Automated Sciences Group, Inc.

Component Level

Decision Types

1. Frequency, Extent, and Technology of Inspection: decide when a facility component requires inspection in order to maintain its prescribed level of operation. Is this decision based on a time interval or a performance standard? Decide what level of inspection information is required for a particular component and what level of dollar investment this will require. Determine what physical information about the component will be needed to provide this condition information. Determine equipment and instrumentation needed to provide this information.

2. Repair/Replace/No Action: based on the condition of the component, decide if it should be repaired, replaced, or left alone. If it should be repaired, determine how much money should be spent to repair it. Determine the dollar threshold above which repair is no longer the best option and replacement is needed.

Information Requirements

1. Physical Characteristics: the actual physical characteristics of the component must be known (i.e., shape, dimensions, materials, age, rated capacities). Line drawings are useful in showing these representations.

2. Condition and Performance Rating: the in-situ condition of the component, in terms of both physical condition and performance criteria, must be compared with standard criteria for a component. These criteria can be defined in physical terms (gallons per minute of flow through a pipe, load-carrying capacity of concrete in psi) or performance terms (e.g., number of roof leaks in a year). The use of condition indexes at the component (or subcomponent) level is also appropriate (as in ROOFER, where an overall roof condition index [RCI] is derived from the condition indexes of subcomponent parts--flashing, membrane, and insulation). Roofing is considered a building (facility) component whereas the flashing, membrane, and insulation are subcomponents of the building.

3. Diagnosis of Condition Cause: determination of the condition of a component and the cause of substandard conditions. Serves as input to models that predict future conditions.

4. Projection of Future Life and Performance: needed for developing long-range work plans and budgets.

5. Cost of Maintenance: maintenance expenditures must be predictable, quantifiable, and historically available for individual components.

6. Maintenance Needs: work needs must be identified so that maintenance plans can be developed.

Approach

1. Automation To Aid in Inspection, Condition Sensing, and Data Interpretation: refers to technology that can rapidly capture inspection data and transfer it to a data base in a meaningful way.

At the component level, automated data entry and ease of integration into the data base are the key issues. Large amounts of detailed information about individual components must be entered into the data base, interpreted, and related to other decision levels. A variety of inspection and testing methods must be used to determine the in-situ condition of individual components. There are cases where visual inspection is adequate; in other cases, additional nondestructive testing and remote sensing are required to determine component condition (e.g., infrared thermography for built-up roofing). Data collected from the inspections (visual or other NDT methods) must be assembled and interpreted. The interpretation of inspection data results in a diagnosis of component condition.

2. Life-Cycle Cost Analysis: based on the diagnosis, determine the most cost-effective way to use and maintain the component.

Technology

1. Machine Vision: refers to automated imaging and image interpretation technology which are currently used in manufacturing to automate component inspection.

2. Nondestructive Evaluation Methods: refers to a class of methodologies developed in manufacturing, aerospace, and nuclear industries for detailed analysis of component condition.

3. Geophysical Techniques: refers to a class of techniques developed for evaluating Earth materials. These methods are being adapted for inspection of concrete and soil structures.

4. Expert Systems: computer software automating the interpretation of sensor data. Very few systems are currently available addressing component inspection.

5. CAD: software used to generate graphic representations of data stored in the inspection and condition data base. A wide variety of CAD packages is available for both mini- and microcomputer environments. Currently, however, they are typically not capable of easy integration into a relational data base environment with geographic and visual information.

6. Voice Systems: a system for translating human voice patterns into a data base. This system speeds the visual inspection process by eliminating the need to record information manually. The VOIS® system is commercially available from Automated Sciences Group, Inc.

APPENDIX D:

SUMMARY OF NONDESTRUCTIVE EVALUATION METHODS FOR INSPECTION OF BUILDING MATERIALS

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
1. Acoustic Emission	During crack growth or plastic deformation, the rapid release of strain energy produces acoustic (sound) waves that can be detected by sensors attached to the surface of a test object.	Continuous monitoring of structure during service life to detect impending failure; monitoring performance of structure during proof testing.	$10,000 for single pick-up, up to $100,000 for multi-channel pickup.	Extensive knowledge required to plan test and to interpret results.	Monitors response of as-built structure to applied load; capable of detecting onset of failure; capable of locating source of possible failure.	Requires means of loading structure; complex electronic equipment is required; access to surface is required.
2. Acoustic Impact (Hammer Test)	Surface of object is struck with a hammer (usually metallic). The frequency and damping characteristics of the "ringing" can indicate the presence of defects.	Detect delaminations or disbonds in composite systems; detect voids and cracks in materials, e.g., hammer technique to detect defective masonry units; "chain drag" method to detect delaminations in concrete pavements.	Negligible for manual technique, $3000 for measuring devices.	Low to use, but experience needed for interpreting results.	Portable; easy to perform test; electronic device not needed for qualitative results.	Geometry and mass of test object influences results; poor discrimination; reference standards required for electronic testing.
3. Cast-in-Place Pullout	Measure the force required to pull out steel rod with enlarged head cast in concrete. Pullout forces produce tensile and shear stresses in concrete.	Estimation of compressive and tensile strengths of concrete.	$1000 to $4000.	Low, can be used by field concrete testers and inspectors.	Only NDE method which directly measures in-place strength of concrete. Appears to give good prediction to concrete strength.	Pullout devices must be inserted during construction. Cone of concrete may be pulled out, necessitating minor repairs.
4. Cover-Meter	Presence of steel affects the magnetic field of a probe. Closer probe is to steel, the greater the effect. Principle of operation is similar to eddy current method.	Determination of presence, location and depth of rebars in concrete and masonry units.	$800 to $1500.	Moderate. Easy to operate. Need training to interpret results.	Portable equipment, good results if concrete is lightly reinforced.	Difficult to interpret results if concrete is heavily reinforced or if wire mesh is present.
5. Eddy Current	An electrically excited coil induces eddy current flow and an associated electromagnetic field in metal. Flaws alter induced electromagnetic field which in turn alters the impedance of the excitation coil. Change in coil impedance indicates presence of flaw or anomaly.	Inspection of metal parts for cracks, voids, inclusions, seams, and laps; measurement of thickness of nonmetallic coating on metals; detection of improper alloy composition.	Minimum of $3000.	Moderate.	Extremely sensitive to change in properties and characteristics of metal; portable.	Requires calibration with standards; limited depth of penetration; only applicable to metals; sensitive to geometry of part.

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
6. Electrical Potential Measurements	Electrical potential of steel reinforcement measured. Potential indicates probability of corrosion.	Determining condition of steel rebars in concrete.	$1000 to $2000.	Moderate. User must be able to recognize problems.	Portable equipment. Field measurements readily made. Appears to give reliable information.	Does not provide information on rate of corrosion. Requires access to reinforcing bars.
7. Fiberscope (Endoscope)	Bundle of flexible, optical fibers with lens and illuminating systems is inserted into small bore hole--permits view of interior of cavities.	Check condition of materials in cavity, such as thermal insulation installed in wall cavities, pipes and electrical wiring in cavity walls; check for unfilled cores in reinforced masonry construction; check for voids along grouted stressed tendons.	$3000 to $6000.	Low.	Direct visual inspection of otherwise inaccessible parts is possible.	Probe holes usually must be drilled; prove holes must connect to a cavity.
8. Gamma Radiography	Gamma radiation attenuates when passing through a building component. Extent of attenuation controlled by density and thickness of the materials of the building component. Photographic film record usually made, which is analyzed.	Locating internal cracks, voids and variations in density and composition of materials. Locating internal parts in a building component, e.g., reinforcing steel in concrete.	$5000 to $10,000.	Must be operated by trained and licensed personnel.	Portable and relatively inexpensive compared to x-ray radiography; internal defects can be detected; applicable to a variety of materials.	Radiation intensity cannot be adjusted; long exposure times may be required; dangerous radiation; two opposite surfaces of component must be accessible.
9. Indentation Hardness Test	Pointed probe is mechanically forced into surface of a material, usually a metal, under a specified load. The depth of indentation is measured, and strength of material may be estimated.	Determination of effectiveness of heat treatment on hardness of metals. Estimating tensile strength of metals.	$600 to $4000.	Low.	Portable equipment available; fast and easy test to perform.	Conversion tables give only approximate tensile strengths; feasibility of testing limited by size and geometry of component.
10. Leak Testing	Telltale substances added to piping system under pressure reveal presence of leaks. Sound amplification to detect leak noise.	Detection of leaks in pipes carrying fluids.	Wide range depending on detection method. $100 to $5000.	Low to high depending on application.	Can locate leaks too small to be found by any other NDE method.	Difficult to determine position of leaks in pipes hidden in wall or floor cavities.

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
11. Liquid Penetrant Inspection	Surface is covered with a liquid dye which is drawn into surface cracks and voids. Developer is applied to reveal presence and location of flaws.	Detection of surface cracks and flaws. Usually used to inspect metals.	$50 to $250 per 100 linear feet of inspection.	Low.	Inexpensive; easy to use; can be applied to complex parts; results are easy to interpret.	Detects only surface flaws; false indications possible on rough or porous materials; surface requires cleaning prior to testing.
12. Magnetic Field Testing	An electrically energized primary coil is brought near test object. A voltage is induced in a secondary coil, and its magnitude is compared to a reference standard. Magnetic properties of test object affect induced voltages.	Distinguishing between steels based on differences in composition, hardness, heat treatment, or residual stresses; locating hidden magnetic parts; measuring thickness of nonmagnetic coatings or films.	$3000.	Low to moderate, depending on application.	Portable; rapid test; easily detects magnetic objects even if embedded in nonmagnetic material.	Applicable only to ferromagnetic alloys; reference standards and calibration may be required for some applications.
13. Magnetic Particle Inspection	Presence of discontinuities in ferromagnetic material will cause leakage field to be formed at or above the discontinuity when the material is magnetized. The presence of the discontinuity is detected by use of finely divided ferromagnetic particles applied over the surface. These form an outline (termed indication) of the discontinuity.	Used most often to detect fatigue cracks in in-service metal components and inspection during production control. Applicable to inspecting welds.	Minimum of $2000.	Expertise required to plan nonroutine tests. Moderate expertise to perform test.	Capable of detecting subsurface cracks if they are larger than surface cracks, size and shape of component poses no limitation; portable equipment available.	Non-ferromagnetic metal cannot be inspected; coatings affect sensitivity; demagnetization may be required after testing.
14. Maturity Concept	The early age strength development of concrete is related to the combined effect of temperature and time.	Prediction of the compressive strength of concrete during the construction phase.	Maturity meter costs around $2000.	Expertise required to develop maturity-strength relationships.	Accounts for in-place temperature history. Field measurements simple to perform.	Calibration strength--maturity curve must be developed. No direct measure of in-place strength. Location of temperature sensors must be carefully selected.
15. Moisture Meter--Capacitance	Water affects the dielectric constant and the dielectric loss factor of materials. Measurement of either property can be used to estimate moisture contents.	Measurement of moisture contents of timber and roofing materials.	$1500	Low to use but experience needed to plan test.	Portable; simple to operate; effective over a wide range of moisture contents.	Measurement is only of surface layer; calibration required; results affected by roofing aggregates; many factors affect accuracy.

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
16. Moisture Meter--Electrical Resistance	Electrical resistance between two probes inserted into test component is measured. The resistance decreases with increased moisture contents.	Measurement of moisture contents of timber, roofing materials, and soils.	$300 to $1000.	Low.	Equipment is inexpensive, simple to operate, and many measurements can be rapidly made.	Not reliable at high moisture contents, needs to be calibrated, precise results are not usually obtained.
17. Moisture Meter--Neutron	Fast neutrons are slowed by interactions with hydrogen atoms. Backscattered slowed neutrons are measured, the number of which is proportional to the number of hydrogen atoms present in a material.	Moisture content measurements of soil and roofing materials.	$4000 to $6000.	Must be operated by trained and licensed personnel.	Portable; moisture measurements can rapidly be made on in-service materials.	Only measures moisture content of surface layers (50 mm), dangerous radiation, hydrogen atoms of building materials are measured in addition to those of water.
18. Nuclear Density Meter	Gamma rays are used to measure mass density. The energy loss of the emitted gamma rays is proportional to the mass density of the material through which the rays pass.	Measurement of density of soils.	$4000 to $6000.	Must be operated by trained and licensed personnel.	Portable, density measurements can be made without disturbing the soil.	Calibration necessary, dangerous radiation; only measures density of surface layers.
19. Pin Hole (Holiday) Detector	One electrode is connected to a conductive substrate, another electrode (a moistened sponge) is passed directly over a coating. An alarm is sounded when a pin hole (holiday) is encountered which completes the electrical circuit.	Determining the presence of pin holes in nonconductive coatings over metals.	$200	Low.	Simple to operate; portable.	Results are qualitative, e.g., there is no measure of the size of the pin hole.
20. Proof Loading	Structure or system is subjected to loads and response is measured.	Determining safe capacity and integrity of structures. Leak testing of pressure vessels and plumbing.	Wide, depending on application; often high.	Depends on nature of tests; can be high.	Entire structure can be tested in its "as-built" condition.	Can be very costly, instrumentation required to measure response; careful planning required, can damage structure.

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
21. Rebound Hammer	Spring-driven mass strikes surface of concrete and rebound distance is given in R-values. Surface hardness is measured.	Estimation of compressive strength, uniformity and quality of concrete.	$250 to $600.	Low, can be readily operated by ordinary field personnel.	Inexpensive. Large amount of data can be quickly obtained. Good for determining uniformity of concrete.	Results affected by condition of concrete surface. Does not give precise prediction of strength.
22. Seismic Testing	Integrity of material evaluated by analysis of shock wave transmission and effects. Shock wave induced by explosive charges and transmission detected by transducers.	Determination of soil densities and variation in densities. Also vibrational characteristics of buildings can be determined.	Wide, depending on amount of information desired.	Experience required to plan test and to interpret results.	Large area of soil and entire structure in its "as-built" condition can be tested.	If incorrectly placed, explosive charge could damage structure. Care must be exercised in handling explosives.
23. Thermal Inspection	Heat sensing devices are used to detect irregular temperature distributions due to presence of flaws or inhomogenities that have different impedances to heat flow in the material or component. Contours of equal temperature (thermography) or temperatures (thermometry) are measured over the test surface with contact or noncontact detection devices. A common detection device is an infrared scanning camera.	Detection of heat loss through walls and roofs; detection of moisture in roofs; detection of delaminations in composite materials.	$30,000 for infrared scanning camera. Less expensive hand-held equipment becoming commercially available.	Moderate to extensive depending on nature of test.	Portable; permanent record can be made; testing can be done without direct access to surface and large areas can be rapidly inspected using infrared cameras.	Costly equipment; reference standards needed, means of producing thermal gradient in test component or material is required.
24. Tooke Gage	A V-groove is cut into the coating, and an illuminated magnifier equipped with a reticle in the eyeplace is used to measure the number and thickness of the films.	Measurement of the number and thicknesses of paint layers.	$130[illegible]	Low.	Simple to operate; portable; measurement can be made with any type of substrate.	Small scratch is made in coating and the substrate is exposed.
25. Ultrasonic Pulse Echo	Pulsed compressional waves are induced in materials, and those reflected back are detected. Both the transmitting and receiving transducers usually are contained in the same probe.	Inspecting metals for internal discontinuities. Some work has been performed on the use of the pulse echo method to inspect concrete.	Minimum of $5000.	High level of expertise required to interpret results.	Portable, internal discontinuities can be located and their sizes estimated.	Good coupling between transducer and test substrate critical, interpretation of results can be difficult. Calibration standards required.

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
26. Ultrasonic Pulse Velocity	Based on measuring the transit time of an induced pulsed compressional wave propagating through a material.	Estimation of the quality and uniformity of concrete.	$4000 to $6000.	Low level required to make measurements.	Excellent for determining the quality and uniformity of concrete. Test can be performed quickly.	Does not provide precise estimate of strength. Still required in analysis of results. Moisture variations can affect results.
27. Windsor Probe	Probe fired into concrete and depth of penetration is measured. Surface and subsurface hardness measured.	Estimations of compressive strength, uniformity, and quality of concrete.	$1000 plus cost of probes.	Low, can be operated by ordinary field personnel.	Equipment is simple and durable. Good for determining quality of concrete.	Slightly damages small area. Does not give precise prediction of strength.
28. X-ray Fluorescence Analyzer	Material is irradiated with a radioactive isotope and absorbed energy is re-emitted as X-rays characteristic of elements present in material.	Determination of the elements present in material.	$7000 to $20,000.	Extensive knowledge of technique required for calibration; moderate to conduct field tests.	Rapid analysis; test can be performed on installed materials; portable.	Periodic calibration with reference standard required, not capable of detecting all elements; analysis of small region per test.
29. X-ray Radiography	Similar to gamma radiography, except X-rays are used.	To identify hidden construction features in wooden structures.	Field equipment is probably over $5000.	Should be operated by trained personnel because of radiation.	Portable equipment available, intensity of radiation can be varied.	Dangerous radiation; portable units have low intensities and field applications limited to wooden and thin components; opposite surface of component must be accessible.

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