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Real-Time Imaging for Construction Site Metrology

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Military construction, like private industry, needs improved methods by which: (1) quality can be assured throughout the construction process, (2) the degree of construction progress can be assessed and documented, and (3) the performance of systems and materials can be assessed over time to aid in maintenance decision-making. Although these aspects of construction processes have traditionally been addressed through an empirical approach, recent advances in computer technology have provided new opportunities for improving upon the traditional methods. The U.S. Army Construction Engineering Research Laboratory (USA-CERL) is exploring the use of a sequential construction analyzer (SCA) to improve quality assurance, allow for more effective tracking of construction progress, and provide data for making decisions about maintenance. The SCA is a computer-based system that uses images obtained via various types of cameras to enhance the image data into useful information.

This study was conducted to identify potential applications of the SCA in three areas of construction: buildings, construction sites, and paving. Many possibilities exist for applying this technology to the construction industry. The SCA concept is being optimized at USA-CERL, and a prototype is under development. When the prototype has been field-tested successfully, it will be used to develop specific applications for the Army and private industry.

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FOREWORD

This work was performed for the Directorate of Engineering and Construction, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Project 4A162731AT41, "Military Facilities Engineering Technology"; Work Unit BO-042, "Techniques to Improve QC/QA Effectiveness." The HQUSACE Technical Monitor was Richard Carr, CEEC-CE.

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COL Carl O. Magnell is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

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REAL-TIME IMAGING FOR CONSTRUCTION SITE METROLOGY

1 INTRODUCTION

Background

The U.S. Army Corps of Engineers (USACE) is responsible for a wide range of construction functions involving buildings, dams, waterways, aircraft runways, and other projects. For each type of construction. there is a need within USACE as well as in the private sector for improved methods by which: (1) quality can be assured throughout the construction process, (2) the degree of construction progress can be assessed and documented, and (3) the performance of systems and materials can be assessed over time to aid in maintenance decision-making. Traditionally, these aspects of construction processes have been addressed empirically, largely through visual assessments and a wide range of reporting formats.

In an effort to reduce construction costs to USACE, quality assurance (QA) personnel have become responsible for assuring quality on an increasingly large number of technically diverse projects. Although QA personnel's time on projects has decreased with the growing demand on their time, the necessary documentation and awareness of project construction processes has not. To enable QA personnel to maintain excellence in field work, their capabilities need to be enhanced and optimized through state-of-the-art technology.

One method of optimization is to gather QA information over some time span by acquisition and analysis of images gathered using various cameras. The images and analysis can then be reviewed by QA personnel when time permits. These captured images could be stored for documentation or further processed through special techniques to produce information that previously relied on labor-intensive methods. For example, an image could be processed to highlight and calculate an area that changed from a previous image. QA personnel could then use their time to interpret the information already processed and make decisions when necessary. This approach would optimize their time by permitting them to be in the field longer and freeing them from time-consuming data analysis which could be performed by computers.

Recent advances in computer technology have expanded the opportunities for improving and enhancing traditional QA methods. The U.S. Army Construction Engineering Research Laboratory (USA-CERL) is exploring an image-processing concept called the sequential construction analyzer (SCA) to improve quality assurance, assist in tracking construction progress, and provide data for maintenance decision-making. This work is part of USA-CERL's long-term research into real-time methods of QA at construction sites. The SCA is a computer-based system that quantifies and stores images, such as those obtained photographically using either visible or thermal emanations. The SCA's image-processing capabilities include enhancement or modification of the image to improve its appearance or highlight information; measurement of image elements; classification or matching of image elements; and recognition of items in the image.

The SCA is intended to enhance QA personnel's capabilities while providing a way to improve documentation and tracking of construction processes. Although the prototype system will focus on QA during construction, many other applications are likely in the future. Potential applications range from planning and design processes, through construction, to the operation and maintenance (O&M) stage of a project.

Objective

The objective of this study was to identify the capabilities and potential applications of image processing in construction-related areas of primary interest to USACE: buildings, construction sites, and pavements. The emphasis was to be on QA activities, with a secondary goal of outlining an approach by which other potential applications can be identified.

Approach

The approach taken by USA-CERL was to:

1. Identify military QA personnel needs that might benefit from a technology like the SCA.

2. Establish the state of the art in imaging technology.

3. Begin developing a prototype SCA to establish: resolution capabilities on a microcomputer-based system using different imaging techniques; the algorithms necessary to perform various image analysis processes; and the relative time and computer memory needed to perform the various analyses for the prototype application as a model for future versions of the SCA.

Scope

Information in this report is a theoretical discussion of the possible USACE applications of image acquisition and analysis throughout the construction process. USA-CERL has developed imaging systems suitable for field work. USA-CERL does not have a packaged system called an SCA, but has the equipment comprising an SCA which can be configured in various combinations to accommodate site-specific applications. Such applications are developed by first analyzing the information/product needed from the SCA. This information is matched through knowledge of the state of the art to the technology available for forming a site-specific SCA.

Mode of Technology Transfer

This report will serve as the basic reference document for future development of QA guide specifications for USACE. It will also provide background in developing potential applications of imaging technology for other aspects of the construction process. This report and demonstrations of the technology will be presented to the Construction Industry Institute's Advanced Technology Institute as a form of technology transfer to private industry.

2 IMAGE-PROCESSING TECHNOLOGY

This chapter presents an overview of the goals and existing technology in the field of image processing. Included are descriptions of: (1) a generic image-processing system that uses a personal computer and an image-processing or graphics board and (2) some of the more commonly used image-processing algorithms.

Image processing is the science of modifying and analyzing pictures. The basic goals of image processing include enhancement or modification of an image to improve its appearance or highlight information, measurement of image elements, classification or matching of image elements, and recognition of items in the image.

Image processing is performed using step-by-step procedures called algorithms. These algorithms are often implemented using computers that are flexible and have relatively low processing and memory costs. The algorithms are expressed as, and become nearly synonymous with, programs for the computer. An algorithm can specify operations such as how to acquire the image. Special image-processing hardware often supplements the computer.

The SCA will rely on image-processing techniques to analyze and transform an image into useful QA information. This information can then be interpreted by humans. To establish the capabilities and applications of the SCA, it is necessary to have a thorough understanding of current image-processing technologies and how they can be combined to produce a useful, functional system.

Terminology for Image Processing

Before discussing the details of image processing, it is important to provide a frame of reference with respect to the terminology used in this report. Because so many branches of science have used image processing independently, people have invented many different terms that describe the same ideas. This report describes applications of computer-assisted image processing in construction using terminology from the computer science and electrical engineering disciplines.

Image-processing Hardware

A minimal generic image-processing system (that could comprise an SCA) consists of a camera, a digitizing circuit, an image memory (a section of computer memory dedicated to holding the image), a computer that can access image memory, and a device that can display the contents of memory (i.e., the picture being processed). Such a system acquires, processes, and displays monochrome images.

The digitizing circuit places a camera image into the image memory. This process involves digitizing a video frame (or other image, such as a photograph) and breaking it into an array of digital intensity values called pixels (short for "picture elements"). If the image is already represented as pixels, as in a computer graphic, image acquisition consists of simply moving the image from disk to the image memory.

The computer reads and writes information in image memory. The display device reads image memory and shows a representation of it. An entire video image stored in image memory is often called a "frame buffer" or "frame store." The most common frame size is derived from the National Television Standard for Color (NTSC) which results in a frame size of 512 by 480 pixels.

Most low-cost computers work with data that is represented by 8 bits (binary digits). In the explanations to follow, assume that a pixel has an 8-bit byte, which means that it can have 2^8 (256) different gray-level intensities. Let 0 represent black and 255 represent white with all the corresponding shades of gray in the range 0 to 255.

The computer manipulates the pixels in the image memory. The display device converts the processed pixels back into spatially organized image intensities. This display device is usually a digital-to-analog (D/A) converter that drives a monochrome or color television monitor.

Classifying Algorithms

Image-processing algorithms can be classified in many ways. If an algorithm changes a pixel's value, it is called a "point process." If the algorithm changes a pixel's value based on the values of (1) that pixel and (2) neighboring pixels, it is called an "area process." If the algorithm changes the position or arrangement of the pixels, it is called a "geometric process." Algorithms that change pixel values based on comparing two or more images are called "frame processes" (because individual video images are called "frames").

Image measurement makes few assumptions about what items are in the picture. Classification and recognition require successively more knowledge about what can appear in an image. For example, the number of pixels in a remote sensing (satellite) image of the Earth having a certain range of values can be measured. If it is known that wheat corresponds to these values, the image can be classified into wheat and nonwheat areas. If the machine is provided with knowledge about the structure of wheat fields, it might be able to recognize these fields in the image. Color could also be used to highlight the recognized areas.

Additional ways of classifying image-processing algorithms include image-based versus symbolic methods, linear versus nonlinear, and the knowledge level used. Image-based algorithms transform pixel values into other pixel values or locations using numerical or logical operations, whereas symbolic algorithms manipulate data that represents knowledge about groups of pixels.

The knowledge level used in an algorithm can range from simple assumptions about the physics of image formation to specific knowledge about possible items in a scene. The above example of wheat field measurement, classification, and recognition illustrates the knowledge-level dimension. Algorithms are image-based, require minimal knowledge about the image contents and, therefore, are not recognition algorithms.

Based on this classification framework and the conceptual hardware, some example algorithms will be described. These examples are not necessarily complete or efficient; they are intended only to facilitate an understanding of the image-processing options for this technology.

Point Processes

A point-process algorithm scans through the image area using the pixel value at each point to compute a new value at that point.

Optical Negative

To produce the photographic negative of an image, the computer is programmed to take each pixel value f ($0 \leq f \leq 255$) and replace it with g where $g = 255 - f$.

Brightness

Point processes also can be used to enhance or modify pixel values. For example, adding 40 to each pixel value brightens the image and could improve the picture's appearance.

If the pixel value and its location are used, then a point process can be used to correct shading or smoothly change pixel values in an image area. Shading is an image artifact caused by slow spatial shifts in scene lighting or camera bias and sensitivity. A point process that computes the inverse of a shading function can eliminate or correct much of this shading.

By smoothly changing the pixel values in an area, the contrast of areas can be highlighted or adjusted. This function can produce results similar to the photographic darkroom techniques of burning and dodging (methods of adjusting the contrast locally).

Histogram Stretching

To calculate an "intensity histogram," the number of times a particular pixel value occurs in an image is counted. Using conceptual hardware based on 8-bit pixels, 256 pixel values are possible. The image can be scanned and the number of times a given pixel value is found counted. The result can be stored as one entry in a 256-place table. Such a table is called a "histogram."

The histogram is an example of image measurement. Because it examines a single pixel at a time, the histogram can also be classified as a point process that leaves the pixel's value unchanged.

Information provided by the histogram is useful for image enhancement and classification. If all pixel values are bunched in a small range (making the picture appear featureless), this information can be used to improve image contrast. Starting at intensity 0, the histogram can be searched for the first pixel value with more than a specified number of pixel counts, say 30. Next, a similar search is performed starting at the highest pixel value. The region of the histogram between these two (low and high) values accounts for most of the pixels in the image. Then a point process is set up that sets pixel values below the low value to 0 and above the high value to 255. This is sometimes called a "histogram clip." The pixels with intermediate values are adjusted so that they span the range of 0 to 255.

Histogram stretching is a simple form of contrast enhancement. Note that the image has lost some information--the pixel values below the low value and above the high value have been set to constants. In general, image-processing operations lose some information in return for selecting or accentuating other information.

Notice that the histogram stretching algorithm used three simpler algorithms: a histogram, a histogram clip, and a point process. Most algorithms are compounds of other algorithms. Therefore, the program writer must know which algorithms to apply and in what order to apply them to reach a processing goal.

Pseudocoloring

Pseudocoloring of a monochrome image is another example of a point process. In this case, the pixel value is the argument (input) for three different functions, and the output of these functions drives the red, green, and blue guns of a color monitor. This process allows a monochrome image to be colored by substituting any color for a particular shade of gray. Of course, using 8-bit pixels, only 256 colors can be displayed at once.

Area Processes

An area process uses information from a neighborhood of pixels to modify pixel values or assert the existence of some property of the neighborhood. Area processes can generate a wide range of effects: spatial filtering (such as filtering out repeated elements), changing an image's structure, or "sharpening" the image's appearance by accentuating intensity changes. Other effects include: finding objects by matching images, measuring image properties, making assertions about object edges in the image, removing noise, and blurring or smoothing the image.

Convolution is a classic image-processing algorithm commonly used for spatial filtering and finding image features. Despite its name, convolution is not difficult to understand. However, since it is computationally expensive, many subtle implementation issues must be considered.

The convolution operation replaces a pixel's value with the sum of that pixel's value plus those of its neighbors, each weighted (multiplied) by a factor. The weighting factors are called the "convolution kernel." The programmer labels the image points p (i,j) and the kernel (weighting) points k (x,y), where x and y range over values representing the relative placement of neighboring pixels.

Choose, as an example, a neighborhood consisting of a pixel plus its immediate eight neighbors (left, right, up, down, and diagonals). Label the center pixel as p (1,1). This center pixel is replaced by the linear sum of its neighbors times their respective weighting factors.

$$
\begin{aligned}
P(1,1) \leftarrow\; & p(0,0) \times k(0,0) + p(1,0) \times k(1,0) + p(2,0) \times k(2,0) \\
& + p(0,1) \times k(0,1) + p(1,1) \times k(1,1) + p(2,1) \times k(2,1) \\
& + p(0,2) \times k(0,2) + p(1,2) \times k(1,2) + p(2,2) \times k(2,2)
\end{aligned}
$$

To convolve an image, this operation is repeated at every pixel position in the image. You can think of this process as sliding a kernel matrix over each row of pixels in the image matrix. At each point, simply multiply the kernel values with the image value "under" it, sum the result, and replace the pixel at the center of the kernel with that value. The equation then becomes:

$$
\begin{aligned}
p(i,j) \leftarrow\ & p(i-1,j-1) \times k(0,0) + p(i,j-1) \times k(1,0) + p(i+1,j-1) \times k(2,0) \\
& + p(i-1,j) \times k(0,1) + p(i,j) \times k(1,1) + p(i+1,j) \times k(2,1) \\
& + p(i-1,j+1) \times k(0,2) + p(i,j+1) \times k(1,2) + p(i+1,j+1) \times k(2,2)
\end{aligned}
$$

Implementation Issues

There are several interesting issues to be met here: Convolving an area of size X by Y with a kernel of size N by M requires X x Y x N x M multiplications and additions. Thus, a 512 by 480 image with a 3 by 3 kernel requires 2,211,840 multiplication/addition operations; this process can take a long time on a computer without fast multiplication hardware.

If the kernel is scanned over the image and replaces only the value under the center of the kernel at a given position, what happens to the edges of the image? For example, with the 3 by 3 kernel, a 1-pixel border (box) is left around the image where pixels are not replaced. The convolution will always leave a border of "garbage" equal to half the kernel size around the image. This border of garbage may be ignored, set to 0, or have the nearest meaningful value copied into it.

The convolution on any pixel could result in a value larger than can be held in a pixel--possibly as large as the number of kernel elements times the number of bits in a pixel. In the generic system described previously, for example, that would be 3 x 3 x 256 = 2304, for which 12 bits per pixel would be needed--but there are only 8 bits per pixel. Enough accuracy in the calculations must be kept to allow for this range. The convolution result can be scaled (e.g., divide each result by 2) if it is to go back into the image memory.

In a related issue, kernel values, and therefore the convolution output, can be positive or negative. Negative intensity is mathematically useful, but not physically reasonable. In this case, negative intensity cannot be displayed. The option to modify the convolution output might be desired such that only positive, negative (negated to positive values), absolute values, or signed values are output. This also means that an additional sign bit must be kept in the calculations. Thus, for 8-bit pixels and a 3 by 3 kernel, 12 bits for the sum and an additional bit for the sign are needed.

Clearly, convolution itself is relatively simple, but the implementation issues complicate it. This condition, unfortunately, is true of most image-processing algorithms. For example, the issues of internal accuracy and what to do at the edge of the image appear in most other area processes. Any useful program must address these issues to implement and use the algorithms effectively.

Matched and Spatial Filters

When applying convolution to a problem in image processing, the program writer should generally think of it as either a matched filter or a spatial filter. In a matched filter, the convolution kernel is essentially a small image of what is to be amplified or detected. For example, suppose vertical edges in the image are to be amplified. An edge is represented in the image by a sudden increase or decrease in image intensity.

Such a kernel looks somewhat like a vertical edge:

```
-1 0 1
-1 0 1
-1 0 1
-1 0 1
-1 0 1
```

Note the effect of the negative values: in a uniform image area, where all pixel values input to the convolution are the same, the convolution output will be 0 (since the sum of any number times each of the 15 kernel elements is 0). The kernel has been padded with a vertical row of zeros to make it an odd size in both directions. This changes the properties of the kernel but is a computational convenience.

A similar kernel for amplifying horizontal edges would look like this:

```
-1 -1 -1 -1 -1
 0  0  0  0  0
 1  1  1  1  1
```

Larger kernels can be used with a pattern (e.g., for the letter A) to detect similar patterns in the image. In this case, the kernel is often called a "template." Detection usually involves amplification of the desired feature followed by a yes/no decision that asks, "Is the result above or below a certain threshold point?"

The other view of convolution is that it performs spatial frequency filtering. In sound, frequency is the number of times per second a waveform repeats. In images, spatial frequency is the concept that an image can be broken down into a series of sine and cosine waves of various frequencies. This breakdown can be done using a fast Fourier transform. The transform should be done both horizontally and vertically because there are spatial frequencies in both directions.

To select, and perhaps detect, a certain band of frequencies, a kernel can be built that selects that frequency band. Quickly changing image intensities are represented by high spatial frequencies, whereas slowly changing intensities are represented by lower spatial frequencies. To select high spatial frequencies, the following kernel could be used:

```
-1 -1 -1
-1  8 -1
-1 -1 -1
```

This is often called a "Laplacian filter" because it approximates an unoriented second-derivative operation. Because edges have high spatial frequencies (sudden intensity changes), this kernel selects edges of any direction. It might be used as an "edge detector" for image analysis.

If the Laplacian kernel is slightly modified by making the center kernel element 9 instead of 8, the result is the same as if the output of the Laplacian convolution were added to the original image (since a kernel with a 1 in the middle surrounded by zeros would yield the source image unchanged). This kernel selectively boosts high frequencies (edges) and the resulting image looks sharper and noisier. On the other hand, if a kernel were used that matches lower spatial frequencies, the image will be blurred.

The power of convolution lies in using information in an area to make assertions about some property at an image point. For example, the edge operators shown above improve the estimate of "edginess" at an image point by using the fact that physical edges extend over some distance. The art of convolving is in picking the right kernel. Experience and theory are necessary for creative convolving.

Nonlinear Area Processes

Convolution is relatively easy to implement, use, and analyze because it is a linear operation: it requires only sums of first-degree products. Nonlinear operations, while a bit more difficult, are also useful and can be more powerful than a convolution. "Powerful" means that they provide a better signal-to-noise ratio for detecting image elements or can detect features with less computation. Consider the following two examples of nonlinear area processes.

Sobel Filtering

A Sobel filter compares the result of two convolutions. The first convolution computes the degree to which an edge exists oriented in the x direction, the second computes the same for the y direction. Simple trigonometry is used to estimate the strength and orientation of edge. The two kernels, X and Y, are:

$$X: \begin{matrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{matrix} \qquad Y: \begin{matrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{matrix}$$

Thus, the edge strength and orientation are represented by:

$$\text{Strength} = \text{sqrt}(X^2 + Y^2)$$

$$\text{Orientation} = \arctan(Y/X)$$

This is a first-derivative (oriented) edge finder, and the vector field it produces cannot be directly shown on a two-dimensional image. The Sobel is a good edge detector and is frequently used as the first step in machine-vision algorithms. Because the Sobel algorithm is computationally intensive, various approximations have been developed to implement it.

Median Filtering

A median filter replaces the pixel at the center of a neighborhood of pixels with the median of the pixel values. The neighborhood values, including the center pixel, are sorted into ascending order and the median (middle) value is used to replace the center pixel. The effect of a median filter is to remove spot noise and low-level noise while retaining larger scale image features.

Pattern and Object Identification

To classify image elements, the computer must be supplied with additional knowledge as to what constitutes an image element. This knowledge can be elaborate, but a simple rule will suffice as an example: an element is a connected group of pixels with the same value. "Connected" means that if the pixel has the same value as a neighbor at 0, 90, 180, or 270 degrees, it is part of the element group.

To simplify the computation, the image can be "binarized"; that is, all pixel values below a threshold value to 0 and all those above the threshold value to 255 can be converted. This is often done in machine vision since it can control the lighting and objects to be viewed. The image is then searched from top to bottom in order to find areas that have more than N connected pixels. By requiring that the area have more than N pixels, the small spots of noise introduced by thresholding can be ignored. Each area is labeled by changing the pixel values in it to a particular pixel value. The number of pixels in an element can also be recorded and used for further classification.

Geometric Processes

Geometric processes change the spatial arrangement of pixels. They are often used to correct for distortions caused by camera optics or viewpoint. They also can enlarge an image area of interest. Typical geometric processes rotate, stretch, and translate the image position. Other geometric processes can warp the image. Geometric algorithms can be expressed by a set of equations (a matrix) that maps a pixel at location x,y into a new address x',y'. For example, to rotate a square area clockwise by 90 degrees, the pixels are mapped by: $x' = (512 - 1) - y$ and $y' = x$.

Because digital pixels are oriented in a strict checkerboard pattern, most geometric transforms are found to have gaps between the output pixels. If source pixels are placed in the destination area according to the transformation equations, the exact placement in the output image is rarely an integer. (This is one problem with digitized images that never occurs in continuous-tone images such as photographic prints.)

Frame Processes

Algorithms that use more than one image are sometimes called "frame processes." A simple example is to subtract one image from another. The resulting differences can be used to compare the two images (e.g., to look for missing parts on a machine or circuit board). Frame processes can also be used to improve image quality and detect motion.

With a television camera to view a static image (i.e., nothing moving in the image), N successive image frames can be summed to reduce noise introduced by the camera. This process requires a frame memory with enough bits per pixel to accommodate the sum. Dividing the sum by N produces an averaged image. If the noise is not correlated from frame to frame, the improvement in signal-to-noise will be of the order sqrt(N). A typical low-cost video camera has about 3 bits of noise, so that averaging with an N of 8 or 16 will noticeably improve the image.

Construction-Related Capabilities

This section contains a broad overview of the image-processing capabilities and how they spring from the basic algorithms. Knowledge of these algorithms and capabilities forms the basis for identifying and establishing applications where this technology is practical and beneficial. Chapter 3 explains their particular usage in construction. The definitions given here are intended to be very general; comprehending the more complex processing techniques requires an understanding of many other theoretical and technical issues (e.g., sampling procedures, lighting, and algorithm stability) and is beyond the scope of this preliminary study.

Skew

The Sobel kernel's sensitivity to edge direction gives an image-processing system the ability to determine if an edge is (1) straight and (2) square to another edge. These characteristics are called "skew."

Documentation of Presence

Using frame processes, an image-processing system can determine the presence or removal of an object in a scene. By using statistical methods or specialized knowledge, it may also be able to determine an object's absence, even if it was never present in a scene.

Nonoptical Images

Image information can be gathered from sources that emit energy other than visible light. Radar, laser, infrared, and other energy forms can yield valuable information.

There are video cameras that sense temperature (via infrared) rather than optical light. An image-processing system uses this information to analyze temperature and secondary causes of temperature change, such as moisture, electrical resistance to current, and exposure to sunlight.

Measurement

Edge detection quickly isolates various objects in a scene. Using other techniques, these objects are identified and measured for length or area. In this way, cracks, voids, object placement, and size can be measured.

Color

Adding color capabilities to image processing generates complicated theoretical issues. Color image processors yield useful information about material cleanliness, material composition, and corrosion.

Roughness

Measuring the statistical characteristics of surface color due to roughness yields diagnosis of a surprising range of material pathologies. Using this technique, researchers have made accurate measurements of delamination, coating cohesion, and subsurface corrosion.

3 SYSTEMATIC ANALYSIS OF IMAGE-PROCESSING APPLICATIONS IN CONSTRUCTION

There are several ways to group image-processing tasks that would be useful in a construction setting, such as: visual medium, visual function, chronological impact on building life cycle, and building subsystem. To present a comprehensive overview, each of these classifications is examined and some possible applications of image processing in construction are discussed.

Classification by Visual Medium

Image information can come from sources other than light in the visual spectrum. Below are examples of nonvisual information that can be supplied to construction activities.

Ground-Penetrating Radar

New types of radar have been developed that can provide information about structures invisible to optical survey. Ground-penetrating radar can detect buried objects and identify soil characteristics.

Thermography

This form of infrared photography is useful for guessing the temperature of objects in an image. By inference, it yields information about electrical conductivity, moisture content, and other processes that can induce temperature change.

Laser Distance Scanning

This form of image, similar to radar, represents the distance to the nearest object for each point in an image. This technique could prove useful in monitoring site excavations.

Laser Interferometry

This form of image information also uses changes in distance. Using two pictures of the same object under slightly different conditions, laser interferometry, because it can resolve extremely small variations between the two images, detects extremely small changes in distance. It can detect the small deflections of structures under varying loads. Hence, one possible application is in evaluating the condition of existing structures.

Classification by Visual Function

Based on the techniques listed in Chapter 2, the following is a list of image-processing abilities applicable to construction. This list is discussed in detail later in this chapter.

1. Documentation of presence. Determines if a particular object is present in an image. Example: has the electrical conduit been installed?

2. Thermal performance. Using thermography, affords the ability to assess material performance via temperature measurement. Example: is concrete being poured during weather that is too cold?

3. Presence of moisture. Using thermography, gives the ability to infer moisture content via temperature. Example: have the roof felts been allowed to become wet?

4. Voids. Gives the ability to assess if an area is completely covered or filled.

5. Cracks. Detects breakage.

6. Cleanliness. Useful in assessing if materials are being handled correctly.

7. Topography. A synonym for roughness. Sometimes a useful measure of material properties or coating quality.

8. Color. Useful for assessing material handling and coatings.

9. Thickness. The ability to measure thickness is useful in determining adherence to various specifications.

10. Composition type. Gives the ability to infer material type and verify its correct usage.

11. Delamination. Allows you to detect when a composite material is separating.

12. Corrosion. Gives the ability to detect the presence of corrosion.

13. Skew. Shows if something is straight and square.

14. Electrical conduction. Via thermography, gives the ability to assess if electrical cabling is overheating, thereby implying an excessive electrical load.

15. Safety. Certain visually detectable events imply the presence of safety hazards (e.g., leaking gas or oil).

16. Terminal overheating. Via thermography, offers the ability to assess the quality of electrical connections.

17. Size. Allows quantitative measurement of length or surface area.

Classification by Chronological Impact on Building Life Cycle

Preconstruction Site Survey and Metrology

Surveys for environmental planning, land use planning, city/urban planning, mapping, and site survey are important, generally understood, and accepted. If the survey process is defined to include impact of construction on preexisting infrastructure, certain survey capabilities could be exploited.

Information gathered via ground-penetrating radar enhances planning by documenting the location of underground pipes, detecting leaks in underground pipes and storage tanks, and evaluating structural status of pavements and railroad track.

Laser interferometry is used to measure (1) differential settlement of bridges and trusses and (2) bridge and pavement deflection under load. Information gathered indicates if preexisting structures can tolerate increased usage.

Construction in Process

The SCA is being developed primarily for the construction process although it could be applied to many other areas. The SCA on a construction site will consist of one or more cameras, strategically located to observe various activities. These cameras will feed pictures to a centralized image processor. The SCA is being designed to perform a range of tasks without user intervention and to keep records for work requiring user help or other ad hoc tasks.

Detailed lists of possible SCA applications for in-process construction are given in tables at the end of this chapter. SCA applications during construction can be broadly grouped as triggers for critical path management events, quality assurance, and supplemental data for construction automation.

When used for critical path management, SCA assists in areas of poor productivity. Construction productivity suffers from lack of proper scheduling, coordination of tool usage, material and engineer availability, and QA scheduling. A finely tuned image-processing algorithm detects construction events that mandate schedule update or change. Examples of this are:

- When the third floor electrical wiring goes in, schedule an appointment with the electrical inspector.
- If the plumbing is not installed on Tuesday, alert the project manager.

QA personnel perform a wide variety of tasks ranging from assuring correct practice of quality control to judging the validity of contractor claims made to the Government for unanticipated costs. To do this work, a QA person must track usage of heavy equipment and other specialized tools (e.g., the contractor might claim the costs of a crane rental on a crane that sits idle). By using ground-penetrating techniques with an SCA, information such as presence of a large metal structure underground can be established prior to sending out a contract for bid. A QA person could then schedule an inspection or require SCA to be in place to allow for verification of the contractor's work required to deal with the structure. Other potential performance measurements include:

- When was the last time the crane moved?
- Are the supply trucks coming in fully loaded?
- Have the roof felts been allowed to become wet?
- How large was that unexpected boulder excavated last week?
- What percentage of this metal panel is corroded?
- Has the paint been applied correctly?

- Is there subsurface corrosion present on this laminate?

- Is that beam straight?

As construction becomes more automated, the SCA could be used for artificial vision. This application would have two principal benefits: augmenting information available to these automatic systems and oversight of tasks to promote safety.

Benefits After Construction

Information retained from the construction process would assist in life-cycle maintenance. By making as-built drawings, recording construction techniques, and automating maintenance management, an SCA would be useful after construction is completed.

Contractors, usually unenthusiastic about producing as-built drawings, could have this requirement semiautomated by feeding pictures of the building (at various stages in construction) to a specialized computer-aided drafting (CAD) program. This program could, with some human help, produce accurate drawings.

As with every form of industrial art, careful planning of task and task order greatly reduces cost and improves results. By the time a need for major repair of a structure arises, some of the techniques used in its construction are outdated or unknown. This makes repair planning difficult and uncertain. Records from image processing could be retained on compact, stable, and easy-to-store media (such as compact disks or video disks). Access to these records would make repair planning easier and more certain.

Optical records of construction and maintenance activities would be invaluable data for automated maintenance management systems. These systems require a composite index of structure condition. Such indices are much more difficult to formulate without detailed knowledge of construction techniques (and hence, repair techniques).

Usage of automated maintenance management techniques has been, in general, hindered by the large amount of time invested in making the initial assay of structures. Image records kept during the construction process could be used to avoid these costly assays.

Not only would selected construction tasks benefit from image-processing applications, but the data collected from these applications would greatly aid life-cycle maintenance. Still other image-processing applications would benefit site planning. Because of the high-speed image acquisition and analysis possible with new and emerging microcomputers, real-time or quasi-real-time evaluation and decision support are possible.

Classification by Building Subsystem

To survey potential SCA applications, this section addresses three major areas of the construction industry of interest to USACE: building construction, construction sites, and paving. These potential applications are detailed in tables that (1) divide each construction process into its major elements, subelements, and materials, and (2) identify major properties or attributes of interest. Within each table, a numbering code is used to identify a potential SCA application and the most likely method by which an image portraying the application can be generated. For example, the number code "1" denotes the use of a video camera and the number code "2" denotes a thermographic camera.

Buildings

A building can be divided into five major elements or subsystems: (1) exterior envelope, (2) interior space divider, (3) electrical subsystem, (4) plumbing subsystem, and (5) space heating and cooling subsystem. Each of these elements can be further divided into subelements and materials. For example, subelements of the exterior envelope are roof, wall, doors and windows, foundation, and floor. Applications of the SCA for these five major elements are described in the following paragraphs with more details in accompanying tables.

Exterior Envelope. Table 1 lists, on the vertical axis, the subelements and materials for the exterior envelope of a building and, on the horizontal axis, key system and material properties or attributes. Major subelements of the exterior envelope are those listed above. Properties or attributes are divided into system and material properties. System properties could be assessed by the SCA on the completed subelement and include skew, documentation of presence, thermal performance, and presence of moisture.

To illustrate the use of the table, examples from the first four vertical columns of Table 1 are cited. Video camera photographs (Code Number 1) can be used to document or assess skew of all completed exterior envelope subelements (listed as "system" under each subelement) and components of some subelements (e.g., decking and structural members of the roof). Video camera photographs can also be used to document the presence of all subelements and other components or materials. This use of photographs may be helpful to inspectors in ensuring compliance with specifications throughout the construction process. Thermographic photographs are likely to be useful in assessing thermal performance of completed exterior envelope subelements, such as the roof, wall and doors, and windows.

In the fourth column, titled, "presence of moisture," both video and thermographic photographs may be useful in documenting the presence of moisture. For example, moisture on or in the completed roof could be detected photographically by video camera if water is ponded on a flat roof or by aerial thermographic photographs if the presence of water is not so obvious. The presence of excessive moisture in insulation of roofs and exterior walls might best be detected by exposing the insulation and documenting the moisture with a video camera.

Interior Space Dividers. Table 2 illustrates potential QA applications of the SCA for subelements and components or materials of interior space dividers. Major subelements of interior space dividers are ceiling, wall, floor and stairs.

As for the subelements and materials of the exterior envelope, video camera photographs can be used to document the presence and the type or composition (e.g., gypsum board, tile or wood ceiling; clear or pigmented coating) of all subelements, components and materials of interior space dividers, assuming photographs are taken while items of interest are visible. Numerous other potential applications are listed in Table 2.

Electrical Subsystem. Table 3 shows potential SCA applications for the electrical subsystem of buildings. Major subelements of the electrical subsystem include (1) service entrance, (2) branch circuits, and (3) other.

Table 1

Quality Assurance Applications of the Sequential Construction Analyzer in the Exterior Envelope of Buildings

BUILDING ELEMENT		SYSTEM PROPERTIES			PROPERTIES OR ATTRIBUTES[1] — MATERIAL PROPERTIES								
EXTERIOR ENVELOPE	Skew	Documentation of presence	Thermal Performance	Presence of Moisture	Voids	Cracks	Cleanliness	Topography (Roughness)	Color	Thickness	Type or Composition	Delamination	Corrosion
ROOF													
System	1	1	2	1,2	-	-	-	-	-	-	1	-	-
Exterior coating	-	1	-	-	1,2	1,2	1,2	-	1	-	1	1,2	1,2
Membrane	-	1	-	1,2	1	1	1,2	-	1	1	1	1,2	-
Membrane joints	-	1	-	2	2	1,2	2	-	-	-	1	1,2	-
Decking	1	1	-	-	-	-	-	-	-	1	1	-	1,2
Structural member	1	1	-	-	-	-	-	-	-	1	1	-	1,2
Insulation	-	1	-	1	1	1	-	-	-	1	1	-	-
Vapor barrier	-	1	-	1	1	1	-	-	-	-	1	-	-
Interior substrate	-	1	-	1	1	1	1	-	1	1	1	1	1,2
Fasteners	-	1	-	-	-	-	-	-	-	-	1	-	1,2
Seals/flashing	-	1	-	1	1	1	-	-	-	-	1	1	1,2
WALL													
System	1	1	2	1,2	-	-	-	-	-	-	1	-	-
Exterior coating	-	1	-	-	1	1	1	-	1	-	1	1,2	1,2
Exterior substrate or siding (cladding)	1	1	-	-	1	1	1	2	1	1	1	1	1,2
Sheathing or waterproofing	1	1	-	-	1	1	-	-	-	1	1	1	-
Structural member	1	1	-	-	-	-	-	-	-	1	1	-	1,2
Insulation	-	1	-	1	1	1	-	-	-	1	1	-	-
Vapor barrier	-	1	-	1	1	1	-	-	-	-	1	-	-
Interior substrate	1	1	-	1	1	1	1	-	1	1	1	1	1,2
Interior coating/covering	-	1	-	1	1	1	1	-	1	-	1	1,2	1,2
Fasteners	-	1	-	-	-	-	-	-	-	-	1	-	1,2
Seals/flashing	-	1	-	1	1	1	-	-	-	-	1	1	1,2

[1] Numbers refer to the most likely method for generating the image to be analyzed by the SCA: 1-video camera; 2-thermographic camera

Table 1 (Cont'd.)

BUILDING ELEMENT	PROPERTIES OR ATTRIBUTES: SYSTEM PROPERTIES				MATERIAL PROPERTIES								
EXTERIOR ENVELOPE	Skew	Documentation of presence	Thermal Performance	Presence of Moisture	Voids	Cracks	Cleanliness	Topography (Roughness)	Color	Thickness	Type or Composition	Delamination	Corrosion
DOORS/WINDOWS													
System	1	1	2	1	-	-	-	-	-	-	1	-	-
Exterior coating	-	1	-	-	1	1	1	-	1	-	1	1,2	1,2
Base material (glazing)	-	1	-	-	-	1	1	-	-	-	1	-	-
Frame	1	1	-	-	1	1	-	-	-	1	1	-	1,2
Interior coating	-	1	-	-	1	1	1	-	1	-	1	1,2	1,2
Hardware	1	1	-	-	1	1	-	-	-	-	1	-	1,2
Fasteners	-	1	-	-	-	-	-	-	-	-	1	-	1,2
Seals/flashing	-	1	-	-	1	1	-	-	-	-	1	-	1,2
FOUNDATION													
Footing	1	1	-	1	1	1	-	-	-	1	1	-	-
Mat	1	1	-	1	1	1	-	-	-	1	1	-	-
Pile	1	1	-	1	-	-	-	-	-	1	1	-	1,2
Tie beam	1	1	-	1	-	-	-	-	-	1	1	1	1,2
FLOOR													
System	1	1	-	1,2	-	-	-	-	-	-	1	-	-
Structural member	1	1	-	-	-	-	-	-	-	1	1	-	1,2
Sub floor	1	1	-	-	1	1	-	1	-	1	1	1	1,2
Finish flooring	1	1	-	-	1	1	1	1	1	1	1	1	-
Floor coating/ covering	-	1	-	-	1	1	1	-	1	1	1	1	-
Fasteners	-	1	-	-	-	-	-	-	-	-	1	-	1,2
Seals/flashing	-	1	-	-	1	1	-	-	-	-	1	1	1,2

Table 2

Quality Assurance Applications of the Sequential Construction Analyzer in the Interior Space Dividers of Buildings

BUILDING ELEMENT	PROPERTIES OR ATTRIBUTES[1]												
	SYSTEM PROPERTIES				MATERIAL PROPERTIES								
INTERIOR SPACE DIVIDER	Skew	Documentation of presence	Thermal Performance	Presence of Moisture	Voids	Cracks	Cleanliness	Topography (Roughness)	Color	Thickness	Type or Composition	Delamination	Corrosion
CEILING													
System	1	1	-	1,2	-	-	-	-	-	-	1	-	-
Coating/covering	-	1	-	-	1,2	1,2	1	-	1	-	1	1,2	1,2
Substrate 1 (outer-most)	1	1	-	1	1	1	1	2	1	1	1	1	1,2
Structural member	1	1	-	-	-	-	-	-	-	1	1	-	1,2
Insulation	-	1	-	1	1	1	-	-	-	1	1	-	-
Substrate 2 (innermost)	1	1	-	1	1	1	1	2	1	1	1	1	1,2
Fasteners	-	1	-	-	-	-	-	-	-	-	1	-	1,2
Openings	1	1	-	-	-	-	-	-	-	-	-	-	-
WALL													
System	1	1	-	1,2	-	-	-	-	-	-	1	-	-
Coating/covering	-	1	-	-	1,2	1,2	1	-	1	-	1	1,2	1,2
Substrate	1	1	-	1	1	1	1	2	1	1	1	1	1,2
Structural member	1	1	-	-	-	-	-	-	-	1	1	-	1,2
Insulation	-	1	-	1	1	1	-	-	-	1	1	-	-
Fasteners	-	1	-	-	-	-	-	-	-	-	1	-	1,2
Openings	1	1	-	-	-	-	-	-	-	-	1	-	-
Trim work	1	1	-	1	1	1	1	-	1	1	1	1	1,2

[1]Numbers refer to the most likely method for generating the image to be analyzed by the SCA: 1-video camera; 2-thermographic camera.

Table 2 (Cont'd.)

BUILDING ELEMENT	PROPERTIES OR ATTRIBUTES												
	SYSTEM PROPERTIES				MATERIAL PROPERTIES								
EXTERIOR ENVELOPE	Skew	Documentation of presence	Thermal Performance	Presence of Moisture	Voids	Cracks	Cleanliness	Topography (Roughness)	Color	Thickness	Type or Composition	Delamination	Corrosion
FLOOR													
System	1	1	-	1,2	-	-	-	-	-	-	1	-	-
Coating/covering	-	1	-	-	1,2	1,2	1	-	1	-	1	1,2	1,2
Finish flooring	1	1	-	1	1	1	1	1	1	1	1	1	-
Subflooring	1	1	-	1	1	1	-	1	-	1	1	1	1,2
Structural member	1	1	-	-	-	-	-	-	-	1	1	-	1,2
Fasteners	-	1	-	-	-	-	-	-	-	-	1	-	1,2
Openings	1	1	-	-	-	-	-	-	-	-	1	-	-
Trim work	1	1	-	1	1	1	1	-	1	1	1	1	1,2
STAIRS													
System	1	1	-	1	-	-	-	-	-	-	1	-	-
Coating/covering	-	1	-	-	1,2	1,2	1	-	1	-	1	1,2	1,2
Finish flooring	1	1	-	1	1	1	1	1	1	1	1	1	-
Structural member	1	1	-	-	-	-	-	-	-	1	1	-	-
Fasteners	-	1	-	-	-	-	-	-	-	-	1	-	1,2
Trim work	1	1	-	1	1	1	1	-	1	1	1	1	1,2

Table 3

Quality Assurance Applications of the Sequential Construction Analyzer in the Electrical Subsystems of Buildings

PROPERTIES OR ATTRIBUTES[1]

BUILDING ELEMENT	SYSTEM PROPERTIES			MATERIAL PROPERTIES		
ELECTRICAL SUBSYSTEM	Documentation of presence	Conduct of Electricity	Safety	Terminal Overheating	Type or Composition	Size
SERVICE ENTRANCE						
Entrance cable	1	-	1	2	1	1
Breaker/fuse box	1	-	-	-	1	1
Breaker/fuses	1	-	-	-	1	1
Fasteners	1	-	-	-	1	1
Terminations	1	-	1	2	1	-
BRANCH CIRCUITS						
Cable	1	-	1	-	1	1
Receptacles	1	-	1	2	1	-
Switches	1	-	1	2	1	-
Other terminations	1	-	1	2	1	-
Enclosures	1	-	1	-	1	1
OTHER						
Electrical fixtures	1	-	1	2	1	-
Electrical appliances	1	-	1	2	1	1

[1]Numbers refer to the most likely method for generating the image to be analyzed by the SCA: 1-video camera; 2 thermographic camera

Video camera photographs can be used to document the presence and the type or composition of all components or materials. For example, a single photograph of the service entrance cable, including its label, could perhaps be used to document its presence, the type of cable (aluminum, copper), its size, and the fact that it has been terminated in compliance with specifications (safety) to the main power breaker.

Under the property "conduct of electricity," photography is not identified as a direct measurement tool. It could, however, be used indirectly to document the flow of electricity by photographing an operable fixture, such as a light bulb.

Plumbing Subsystem. Table 4 presents potential SCA applications for the plumbing subsystem of buildings. Major subelements of the plumbing subsystem include transport, storage, heating, and functional. Video camera photographs can be used to document the presence, type or composition, and size of all components and materials. For components of the Transport Subelement, the applications listed in Table 4 include skew or slope of piping and spigots. Skew or slope data for valves, restraints, and fasteners are unlikely to be of interest and, therefore, are not shown as potential applications.

Space Heating and Cooling Subsystem. Table 5 shows potential SCA applications for the space heating and cooling subsystem. Major subelements of the space heating and cooling subsystem include (1) generation source, (2) transport, (3) storage, and (4) other. System properties are listed as skew or slope, documentation of presence, leaks, and safety. Examples of safety concerns for generation sources that could be addressed using video camera photographs are distance from flammable materials, venting facilities, and restraints or fasteners.

Construction Sites

Table 6 lists potential SCA applications at construction sites. Elements associated with construction sites are divided into three categories: below grade, ground level, and above grade. Properties or attributes are divided into two main categories: topographical and other. The SCA could be used at construction sites to document, for example, changes in terrain as a result of the construction, changes in vegetation patterns, and slope of terrain.

Paving

Table 7 presents potential SCA applications in paving. Paving elements are listed as: (1) construction base, (2) pavement, (3) drainage system, and (4) safety-related system. Video camera photographs can be used, for example, to document or assess skew or slope of completed construction bases, pavements, drainage systems, and safety-related subelements such as surface markings, signs or markers, edge grading, and guardrails. Likewise, video camera photographs can be used to document the presence of all subelements, as shown in the table.

User Survey of SCA Application Needs

Figure 1 shows the results from surveys conducted during the Huntsville Advanced Construction Management courses. Other field personnel were surveyed as well. The figure shows the relative frequency of responses for potential applications of the SCA in the categories defined by Tables 1 through 6. The inspectors, managers, and QA personnel involved in the course listed specific applications which are grouped here to correspond to tables presented under *Buildings* above. The survey results demonstrate field personnel's perception of where the SCA would benefit their work. In general, the response was very positive.

Table 4

Quality Assurance Applications of the Sequential Construction Analyzer in the Plumbing Subsystem of Buildings

	PROPERTIES OR ATTRIBUTES[1]					
BUILDING ELEMENT	SYSTEM PROPERTIES					
PLUMBING SUBSYSTEM	Skew or Slope	Documentation of presence	Leaks	Corrosion	Type or Composition	Size
TRANSPORT						
Piping	1	1	1	1,2	1	1
Valves	-	1	1	1,2	1	1
Spigots	1	1	1	1,2	1	1
Restraints	-	1	-	1,2	1	1
Fasteners	-	1	-	1,2	1	1
STORAGE						
Tank (interior)	1	1	1	-	1	1
Sink	1	1	1	1,2	1	1
HEATING						
Water heater	1	1	1	-	1	1
Solar collector(s)	1	1	1	1,2[2]	1	1
FUNCTIONAL						
Tub	1	1	1	1,2	1	1
Shower	1	1	1			
Sink	1	1	1	1,2	1	1
Toilet	1	1	1	1,2	1	1
Laundry	1	1	1	1,2	1	1
Dishwasher	1	1	1	1,2	1	1

[1]Numbers refer to the most likely method for generating the image to be analyzed by the SCA: 1-video camera; 2-thermographic camera

[2]Assuming conduits for heat transport fluid are visible from the front surface

Table 5

Quality Assurance Applications of the Sequential Construction Analyzer in the Space Heating and Cooling Subsystem of Buildings

	PROPERTIES OR ATTRIBUTES			
BUILDING ELEMENT	SYSTEM PROPERTIES			
SPACE HEATING AND COOLING SUBSYSTEM	Skew	Documentation of presence	Leaks	Safety
GENERATION SOURCE				
Furnace/burner	1	1	-	1
Stove	1	1	-	1
Heat pump	1	1	-	1
Electrical heaters	1	1	-	1
Air-conditioner	1	1	-	1
Radiators	1	1	-	1
Solar collector	1	1	-	1
Fireplace	1	1	-	1
Fasteners	-	1	-	1
TRANSPORT				
Ductwork	1	1	2	-
Piping	1	1	2	-
Restraints	-	1	-	1
Fasteners	-	1	-	1
Conduction/convection	-	-	-	-
STORAGE				
Tank	1	1	2	-
Wall	1	1	-	-
Rockbed	1	1	2	-
Other	-	1	-	-
OTHER				
Chimney	1	1	-	1
Chimney liners	1	1	-	1

Table 6

Applications of the Sequential Construction Analyzer in Construction Sites

SITE ELEMENTS	PROPERTIES OR ATTRIBUTES[1]					
	TOPOGRAPHICAL PROPERTIES				OTHER PROPERTIES	
	Slope	Depth	Height	Width	Vegetation	Area
BELOW GRADE	1	1	-	1	1	1
GROUND LEVEL	1	-	1	1	1	1
ABOVE GRADE	1	-	1	1	1	1

[1]Numbers refer to the most likely method for generating the image to be analyzed by the SCA: 1-video camera; 2-thermographic camera

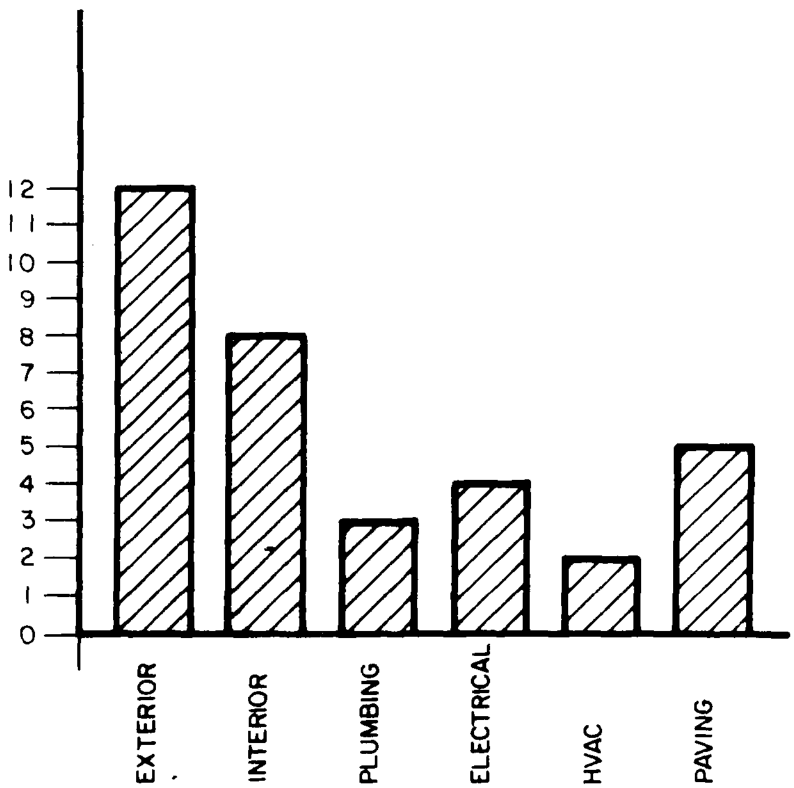

Figure 1. Results of a field survey of potential applications for the sequential construction analyzer.

Table 7

Quality Assurance Applications of the Sequential Construction Analyzer in Paving

PAVING ELEMENTS	PROPERTIES OR ATTRIBUTES[1]: Skew or slope	Documentation of presence	Depth or thickness	Presence of moisture	Voids	Cracks	Topography (roughness)	Color	Composition	Delamination	Corrosion
CONSTRUCTION BASE											
System	1	1	1	-	1	1	1	-	-	-	-
Base materials	-	1	1	-	1	1	-	-	1	-	-
PAVEMENT											
System	1	1	1	-	1	1	1	1	1		-
Matrix	-	1	1	-	1	1	1	1	1	1	-
Reinforcement	-	1	1	-	1	-	-	-	1	-	1[2]
DRAINAGE SYSTEM	1	1	1	-	1	1	-	-	1	-	-
SAFETY-RELATED SYSTEM											
Surface markings	1	1	-	-	-	-	-	1	-	1	-
Signs or markers	1	1	1	-	-	-	-	1	1	-	1,2
Edge grading	1	1	1	-	1	1	1	-	1	-	-
Guard rails	1	1	1	-	1	1	-	-	1	1	1,2

[1]Numbers refer to the most likely method for generating the image to be analyzed by the SCA: 1-video camera; 2-thermographic camera

[2]Assuming visibility of reinforcement

4 DEVELOPMENT PROCESS FOR TYPICAL SCA APPLICATION: OVERVIEW

Numerical Complexities

The most significant factor that determines if an application can be implemented is the number of calculations needed to complete the task. If this number becomes too large, then a computer may not be able to finish the task in an acceptable period of time. At first, this limitation may seem strange. It can be explained in two ways.

When such a linear computer has an image-processing task, it makes calculations on a two-dimensional data domain. As the machine performs more intricate calculations on this two-dimensional domain, the task complexity increases by the square of difficulty of the task. For example, if a program makes calculations on a picture which is a grid of 256 by 256 pixels and then increases the grid size to 512 by 512 pixels, the program executes four times as many calculations rather than twice as many. By taking into account that the image is a two-dimensional representation (a picture) of an event that occurs in three dimensions (construction), the complexity increases further.

Another way of describing why the number of calculations can become overwhelming is to think of the system as a stimulus/response mechanism. The following task illustrates the stimulus/response idea. The domain consists of two cards, one with a black square and one with a black triangle, which can be held one at a time in a standard position and with standard lighting before a camera.

The system is tasked with recognizing which card is being photographed. This task is easy because the system has to differentiate between only two stimuli that can be presented. In a more complicated problem, the computer is required to distinguish a card held in any orientation as long as it is in focus and square to the camera. Assume that the computer can resolve this rotation to within one part in 1000. Now it must distinguish 1000 stimuli out of 2000 (2 cards x 1000) allowable stimuli. This problem is much more difficult than the original one. If changes are allowed in the size of the square, the length of the sides of the triangle, lighting, etc., the problem grows more complicated. If the stimulus is not limited to either a square or a triangle, the number of allowable stimuli becomes astronomical (e.g., with a field of 512 by 480 pixels, each with 8 bits of information, the number of allowable stimuli is $2^{(480 \times 512 \times 8)} = 2^{1966080} = 10^{591849}$.

The above description of the numerical complexities that may be incurred when deriving information via the SCA appear mind-boggling and impractical. However, current technology is at a state that will allow many applications to be achieved in real time. Applications that may benefit from the SCA have to be identified and then, through development, productive enhancement devices made; these applications are possible now.

Two Different Development Strategies

Once a problem is analyzed as being computationally manageable, two main circumstances determine the development strategy of a given SCA application:

1. There is no complete set of image-processing algorithms, i.e., a particular application may or may not be accomplished by simply stringing together a combination of existing algorithms.

2. For any particular set of algorithms that comprise an application, it is difficult (if not impossible) to calculate the anticipated experimental error from a purely theoretical perspective. SCA applications take place under harsh, poorly controlled environmental conditions. The errors introduced by such conditions include: nonuniform lighting for which the system may have difficulty compensating, extreme temperatures that cause the cameras to behave differently, dust and other optical interference, short exposure times due to movement which lower the signal-to-noise ratio, and physical punishment from weather and mechanical abuse. These environmental errors are extremely large compared with algorithm-induced error. Error, therefore, can only be determined experimentally.

Because of these factors, the implementation strategy tends to follow one of two paths. The first path occurs when there are known image-processing techniques sufficient to perform the task with good return on investment. In this case, a program would be prepared to run one or several types of analysis, place the unit in the field, and with the help of a human, run enough trials to determine which method is best and if this best method is good enough. The unit would then be modified to use the best method resulting in a finished product.

The second development path occurs when the correct image-processing techniques are not known and may not be found. When this occurs, it is best to start with a human-guided system. Care must be taken to ensure that the human-guided system yields a good return on investment because there is no guarantee that progress can be made toward an automated system. As algorithms are developed that can handle tasks and task components, they are added to the system, either relieving the human of them or using them as a first approximation to completing the task and allowing the human to edit the results. In this way, the machine eventually can become more and more independent of human intervention, with the ability to do analyses autonomously.

Example of the First Development Strategy

The example involves truck identification at a site entrance. This application consists of setting a camera at the side of the road of a construction site entrance, taking pictures of each vehicle that passes, and, when the picture contains a certain type of vehicle, creating a record of the time and vehicle type.

Because the application is restricted to a small number of vehicle types, there are several image-processing strategies that might work. This application, therefore, should be developed using the first development strategy.

First, pictures of the particular vehicles of interest are taken from the same angle at which the camera will view them onsite. These reference photos are analyzed by looking at the angles of the leading edges on the front end of the truck. Histograms of pixel counts as a function of angle are recorded and stored.

Environmental variables are diminished by using three light beam/photo cell pairs at 10-ft intervals across the roadway at the construction site entrance. If none of the beams are broken, the system takes a snapshot every few seconds as a reference background. If one of the two beams at either end is broken, the system assumes something is coming and retains the previous background shot. When the center beam is broken, the system concludes that it is looking at an item of interest and takes a snapshot.

The background picture is compared with the snapshot to isolate those pixels that actually form the object which broke the beam. The angles on the leading edge of the object's picture are then placed in a histogram (of the same type made for the reference vehicles) and compared with the reference histograms of the truck reference photos. The closest match wins. If none of the reference histograms match well, the system assumes the object is something else and does not count it.

Primitive versions of this application have been developed and tested to identify and count trucks on a construction site. This work was performed by O'Brien in conjunction with the University of New South Wales.[1]

Example of the Second Development Strategy

The example here is for automated pavement analysis. This system, which is currently under development at USA-CERL, is used to analyze pictures of pavement surfaces and forward the resulting analysis to another program called PAVER.

PAVER is a field-tested and validated pavement maintenance management system for use by military installations, USACE Districts, airports, and civilian municipalities. PAVER is designed to optimize the allocation of funds for pavement maintenance and repair. PAVER's key component is a Pavement Condition Index (PCI). The PCI is an objective rating of pavement condition based on observed distress types (cracking, bumps, sags, etc.). The PCI provides a consistent measure of a pavement's structural integrity and operational condition.

Information about a pavement's condition is usually gathered by someone who has to view the pavement, determine which conditions are present, carefully measure the size of the area affected and record all information for later use by PAVER.

The automated pavement evaluation system provides a way for users to cut down this workload. The pavement sections are photographed and the photos fed to an image-processing system. The user works interactively with the system to identify pavement distresses. All other work is left to the computer.

In this application, environmental factors are eliminated by taking the pavement photographs from a camera with a flash unit mounted in the roof of a van with no floor. The van is constructed to completely shade the pavement being photographed. In this way, problems from inconsistent lighting are eliminated.

The image-processing system appears to the user almost like a coloring book. The user views a photograph of a pavement section on a video monitor, tells the system what type of pavement distress appears in the picture, and marks the distress (on the video screen) with a pointing device (i.e., a mouse or a light pen). The system performs all numerical calculations and automatically forwards this information to PAVER. The user makes no numerical measurements, performs no numerical calculations, and needs no manual numerical recordkeeping.

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[1] J. B. O'Brien, J. L. Knott, and R. W. Woodhead, "A System for Fully Automated Capture and Analysis of Field Performance Data," *Organizing and Managing Construction, Volume II: Computer Productivity*, Proceedings, Working Group W-65 (International Council for Building Research Studies and Documentation, 1984).

Because the user is relieved of numerical tallying and recordkeeping, the system saves labor and is of immediate economic benefit. Development of various methods for automatic detection of pavement distresses is under way and will be added to the package as each becomes available. Even if no suitable methods are found, the system is a good investment for its users. This is an example of the second development path because a hand-guided system is justified by return on investment and any autonomous analysis by the system is helpful but not crucial.

5 CONCLUSIONS AND RECOMMENDATIONS

This study has identified the capabilities and potential applications of image-processing technology for military construction. It is clear that there are many potential applications for an SCA that use this technology. Recent advances in the use of computers for image processing hold much promise for construction applications such as quality assurance, tracking construction progress, and obtaining data for maintenance decision-making.

The image-processing concept has been explained briefly. Some of the mathematical algorithms have been presented as having the highest potential for use in construction.

This report has described some potential SCA applications in typical building construction processes. However, opportunities for the use of an SCA are also replete in construction areas such as dams, flood plan surveys, bridge construction, and other points of interest to USACE. The tables in this report suggest an approach by which other opportunities for use of the SCA can be identified; that is, by separating construction processes into smaller subelements, it is possible to assess the individual components for SCA applicability.

To maximize the potential of the SCA, these follow-on activities are recommended:

- Implement a demonstration program to evaluate use of the SCA in construction applications
- Develop guidelines and criteria for using the SCA in construction QA applications
- Identify additional opportunities for use of SCA in construction applications not addressed in this report for development by USACE
- Present information on SCA for contractors as a potential contractor QC tool. Contractors could use the SCA to help prevent deficiencies and tear them out rather than locate them and effect corrective action as would be the case if he SCA is used for QA.

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