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COLOR IMAGE DIGITIZATION AND ANALYSIS FOR DRUM INSPECTION*

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ABSTRACT A rust inspection system that uses color analysis to find rust spots on drums has been developed. The system is composed of high-resolution color video equipment that permits the inspection of rust spots on the order of 0.25 cm (0.1-in.) in diameter. Because of the modular nature of the system design, the use of open systems software (X11, etc.), the inspection system can be easily integrated into other environmental restoration and waste management programs. The inspection system represents an excellent platform for the integration of other color inspection and color image processing algorithms.

INTRODUCTION

At a number of sites, including Savannah River Technical Center, located in South Carolina, low-level waste is stored in 208.2 L (55-gal.) steel drums (waste storage container). A weekly inspection has been mandated by the U.S. Environmental Protection Agency (EPA) to search for rust spots on the exteriors of drums to prevent leakage. The inspection required by the EPA suggested that a human visual inspection of all low-level radioactive storage barrels be conducted weekly. This report describes the development of a color image analysis system designed to identify rust spots in a video image of a waste storage container. The purpose of the off-line color inspection system is to analyze images from an autonomous vehicle with color image collection equipment. The autonomous vehicle would be used to gather weekly pictures of all storage drums. The images would then be transferred to the off-line color image inspection system for analysis. The drums that contain rust spots would then be reported to a human operator.

The system block diagram for the color inspection and analysis system is shown in Fig. 1. The high-resolution RGB camera is connected to a VME-based DataCube Digicolor board, where the color signals are digitized and stored in two DataCube RoiStore boards. The data acquisition system is controlled through a Force M68030 CPU. The operating system selected to control the data acquisition was the VxWorks real-time operating system. The DataCube boards, as well as the VxWorks operating system, were selected in an effort to take advantage of in-house expertise and experience gained from other environmental restoration and waste management (ER&WM) programs.

The DataCube frame-grabber board contains analog filters that limit the color information signal to a 3-MHz bandwidth. This information bandwidth allows the current system to attain the goals of finding rust spots on the order of 0.254 cm (0.1 in.) in diameter. Originally, an S-Video camera was used to capture the color images. The S-Video camera provides a considerable increase in resolution over the RS-170A camera. The DataCube frame grabber put the color signal of the S-Video camera through a 0.5-MHz filter. This limited the information content to what could be obtained with the RS-170A camera, resulting in no increase in resolution. The

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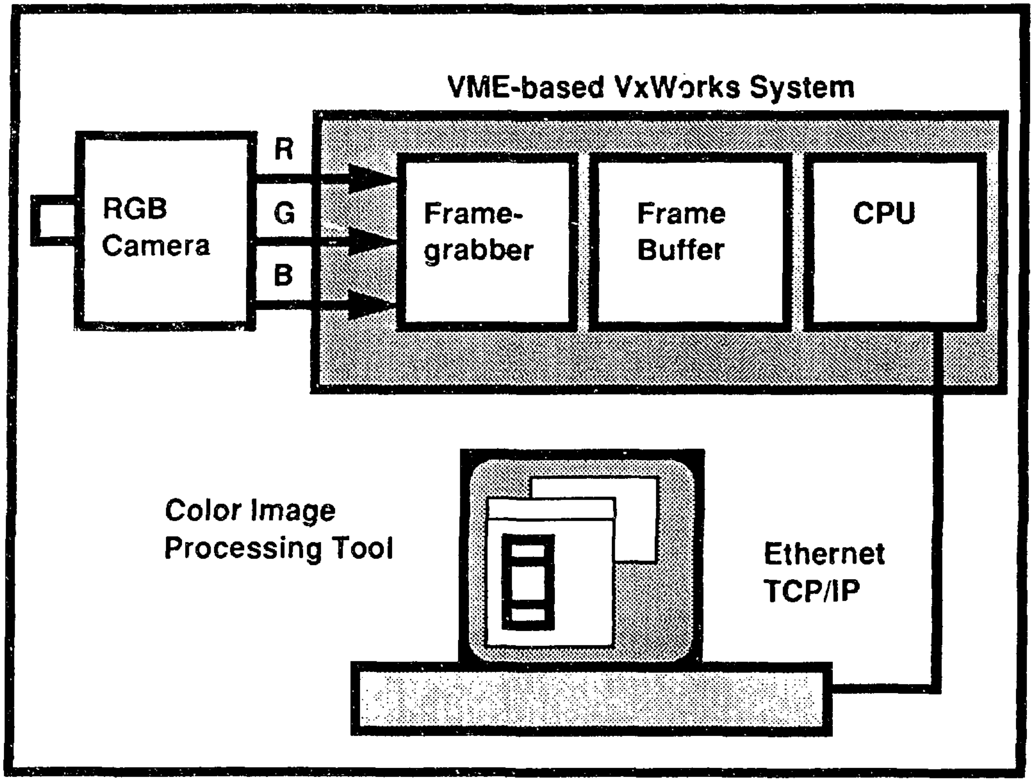

Fig. 1. Inspection system block diagram.

addition of the RGB camera allowed the video system to attain the 3-MHz bandwidth necessary to find rust spots on the order of 0.254 cm (0.1 in.) in diameter.

RUST-DETECTION ALGORITHM

Several algorithms were available to find rust spots, the most prevalent of which was the use of texture analysis. Color was selected initially because of the relative ease in developing color identification algorithms for rust spots (Pratt 1991).

Color may vary somewhat when rust is caused by chemicals eroding the steel from the inside. Simply searching a video image for all values of a particular color (e.g., all reds) and assuming that these red spots indicate potential corroded areas will produce too many potential rust spots in typical images. Consequently, a rust-spot detection algorithm relying upon color to differentiate between rusty and clean regions must use predetermined limits on particular colors or functions of color values to reduce the number of candidate rust spots to a manageable amount. The current algorithm uses limits on the absolute magnitude of the red color as well as the ratio of red to the sum of all of the other colors.

The rust detection algorithm was applied to a video image of a typical waste storage drum. The drum had numerous rust spots that were visible to the casual observer. Initially, the algorithm looked at the absolute magnitude of the red color and the ratio of red to all other colors. Even with heuristic limits, too many rust spots were identified by this algorithm. An additional constraint was added to the ratio algorithm. The second constraint required that a second pixel satisfy the same requirements just to the left and a third one just above the pixel in question. This gave good detection without identifying an excessive number of spurious pixels as rust. However, this further reduced the possible resolution of the inspection system. The image resolution is measured in pixels. (The smallest unit of measure discernible to the video system is one pixel.) The size that the pixel represents in the true image depends is determined by the field of view of the camera. The frame-grabber digitizes one 512 by 512 24-bit RGB image per frame. The test for two adjacent rust pixels increases the confidence of the algorithm but reduces the resolution of the system by a factor of 3.

CAMERA RESOLUTION

The requirements for the color image collection system stipulated that off-the-shelf, commercially available equipment be used. In addition, lower cost was to be of higher priority more than complexity because of the likelihood of contamination. (Once contaminated the costs for cleaning are usually prohibitively high.) The color image collection system should detect rust spots as small as 0.254 cm (0.1 in.) in diameter. The use of color was included to aid the chemists in determining the chemicals that are causing the rust and to identify any chemical leaks. In addition, color analysis was selected as the algorithm to be used to find the rust.

The first step involved determining the type of camera to be used for the test. Three camera protocols are prevalent in the commercial market, National Television Standards Committee (NTSC), S-Video, and RGB. These three standards are compared for resolution. The color NTSC standard is a superset of the monochrome RS-170 standard and is governed by the RS-170A specification (Grob 1984, Negrino 1992, and Lindley 1991).

To meet the RS-170 standard, a video system must have a resolving power of at least 330 lines in the vertical direction and 338 lines in the horizontal direction. Resolving power is the measure of a video system's capability to delineate detail in a video image. These specifications are easily met by most commercially available video cameras and CRT displays. Most video cassette recorders do not have the resolution to meet these specifications. The Super VHS recorder and the newer Super 8-mm recorder go beyond the specification by providing 400 lines of vertical resolving power, thus providing improved picture quality. In general, as the number of horizontal lines are fixed by the specification, the vertical resolving power of the video system should be used for a comparison of resolution.

Examination of the RS-170A specification revealed that the color information had an available bandwidth of ~3.5 MHz. (The typical information bandwidth of the black and white cameras is ~3.5 MHz.) The color cameras that generate RS-170A signals typically limit the color information from 0.5 to 1.3 MHz to reduce the effects of crosstalk without the use of more expensive techniques that would increase the cost of the camera. The black-and-white camera engineers expend more effort on the linearity and resolution designs of their cameras. These design techniques are usually abandoned for techniques that improve current color reproducibility in color cameras. (This serves as one of the strongest arguments for grey-scale image processing over color image processing.) Even though the color information is limited to 0.5-1.3 MHz, the intensity information is still

2 to 3 MHz. However, the smallest discernible color spot becomes the unit of measure for selection of a color camera for rust inspection.

Assuming a 0.5-MHz color information filter on the RS-170A camera, the color resolution was then calculated. The RS-170A camera generates two fields 30 times a second. These fields consist of the even and odd lines that are interlaced to form one frame or picture. The fields contain 262.5 horizontal lines of analog color video information. By combining the fields, one can generate one frame of 525 lines. The horizontal sweep frequency is determined from the number of horizontal lines and the number of frames per second.

30 frames/s X 525 lines/frame = 15,750 lines/s

Horizontal sweep frequency = 15,750 Hz.

Horizontal-line time interval = 1/15,750 Hz = 63.5 us.[a]

The vertical resolving power of a color camera can be calculated if one knows the information bandwidth of the color information signal. The vertical resolving power is a measure of the smallest discernible point along the horizontal axis on the image. If the image consisted of a checker board, the resolving power would measure the smallest size at which the squares are still discernible Assuming that the 0.5-MHz filter is used for the typical RS-170A camera, the time period of filter frequency is 2 us.

Filter time period = 1/0.5 MHz = 2 us.

This is the time to scan two adjacent pixels. The time allotted to one pixel would then be 1 us. With 10.2 us. used for horizontal retrace, only 53.3 out of the available 63.5 us. are available for information display. This translates to a vertical resolving power of 53.3 items per line.

Vertical resolving power = (63.5 – 10.2) us./1 us. = 53.3 lines.

The horizontal resolution can be determined from the RS-170A specification. There are 525 lines per frame. A small portion of these lines, 42, are used for vertical retrace. This leaves 483 lines available for information

[a]NOTE: The actual horizontal frequency and vertical frequency for the RS-170A signal are 15,734.26 Hz and 59.94 Hz, respectively. These frequencies are used to minimize interference between the color subcarrier at 3.579545 MHz and the sound signal at 4.5 MHz.

display. However, not all of the information in the picture may make it to the camera's raster lines. Some of the details are completely missed, while informatic from other pixels shows up in both the even and odd frames. The loss of information during image acquisition is referred to as quantization error. The ratio of the number of raster lines useful in representing picture information content to the total number of visible lines is called the utilization ratio. Theoretical calculations and experimental tests show that the utilization ratio ranges from 0.6 to 0.8. Assuming a utilization ratio of 0.7, the horizontal resolving power of the RS-170A color camera is 338.

Horizontal resolving power = (525 - 42) X 0.7 = 338.1.

The total number of picture elements per frame from these values of vertical and horizontal resolving lines are 18,021 pixels.

Total pixels = 53.3 X 338.1 = 18,020.7.

The total number of pixels per frame available from a 4-MHz filter is ~144K. (A typical 35-mm motion picture frame contains 500K pixels, while a 16-mm frame contains 125K pixels.)

The discernible resolution of an image of a barrel can then be derived.

Delta H = HEIGHT/338.1.

Delta W = WIDTH/53.3.

These values would yield the smallest spot that the RS-170A camera would be able to detect in an image. Everything smaller than this would be averaged into its surroundings. For a resolution of 0.254 cm (0.1 in.), the maximum height and width of the image would have to be no more than 0.858 m (33.8 in.) and 0.541 m (5.3 in.), respectively.

HEIGHT = delta H * 338.1 = 0.10 in. * 338 = 33.8 in.
WIDTH = delta W * 53.3 = 0.10 in. * 53.3 = 5.33 in.

The typical barrel is 0.508 m (20 in.) wide and 0.737 m (29 in.) high. With an aspect ratio of 4:3 and the height of the image required to be at least 0.737 m (29 in.), the width must be 0.644 m (25.35 in.). This results in a resolution of 0.218 cm (0.086 in.) for the vertical resolution and 1.209 cm (0.476 in.) for the horizontal resolution. (The camera is turned on its side to take advantage of the 4:3 aspect ratio but this was not done with the equations to alleviate some possible confusion.)

Delta H = 29 in. / 338.1 = 0.086 in. (0.218 cm)
Delta W = 25.35 in. / 53.3 = 0.476 in. (1.209 cm)

The resolution along the width of the image does not meet the specification. In addition, these values allow no margin for error because of effects such as camera focus and field of view variations caused by positional error in the autonomous vehicle. In addition, the Nyquist sampling criteria require that the sample period be at least half the period of the signal being sampled.

The typical S-Video camera provides 3.5-MHz information bandwidth on the color signal. This increases the resolution obtainable by the RS-170A camera by a factor of 7. Assuming that the horizontal resolving power is the same as the RS-170A specification, the 3.5-MHz bandwidth yields a vertical resolving power of 373 lines. The comparison of camera resolutions is shown in Table 1.

Delta H= 29 in./338.1= 0.086 in. (0.218 cm)
Delta W= 25.35 in./373=0.068 (0.173 cm)

Table 1. Camera Resolution

	RS-170A	S-Video
Vertical resolution	0.086"	0.086"(Horizontal resolving power)
Horizontal resolution	0.476"	0.068"(Vertical resolving power)

Even though these approximations of the S-Video camera yielded satisfactory results, the DataCube frame-grabber put a 0.5-MHz filter on the S-Video color signal to reduce aliasing. This reduced the color resolution of the S-Video to that achievable by RS-170A. This necessitated the use of an RGB camera. The DataCube put 3-MHz filters on each of the RGB color signals. This produced color resolution of ~0.1 in.

COLOR IMAGE PROCESSING TOOL (CIPT)

The CIPT inputs images in Sun Microsystem's rasterfile format and a custom blue, green, red (BGR) format for reading the 24-bit from the DataCube color frame grabber. Color analysis is used at the VME-based system to find the rust spots by taking the ratio of each pixel against the color red and then thresholding the ratio against a predetermined limit. Up to 100 rust locations are stored at the end of the BGR formatted image. After color analysis is performed on the image, the image is sent to the CIPT for further processing and display.

The CIPT color image processing algorithms include averaging, median filters, pseudomedian filters and frequency domain filters. Enhancement of the color images is performed by histogram equalization. The enhancement algorithm is used to improve contrast in dimly lit images. Frequency-domain algorithms include Butterworth lowpass, highpass, and band reject filters. The frequency domain filters are applied to fourier transforms of the time-domain images. The filters are designed to work in one of four color spaces: RGB, IHS, XYZ, and LAB (Gaskins 1992, and Wilson 1988). CIPT allows the choice of any component of any space to be displayed for operator inspection. The majority of the filters operate on the brightness or luminosity component (or its equivalent) of the selected color space. The color space is selected from the color space menu at the top of the window.

The IHS color space is composed of components of intensity, hue, and saturation. Hue is the measurement of color. The saturation is inversely proportional to the amount of white in the hue. The intensity is the measure of luminosity. IHS space is the most prominently used color space for performing color image analysis (Kay 1988, and Genz 1988).

The XYZ color space has been developed as an artificial standard by the Commission Internationale de l'Eclairage (C.I.E.). The XYZ color space was developed to create a color space in which all tristimulus values required to match colors are positive. The mapping from the standard RGB color spaces to the XYZ color space is a linear transformation. The Y component is equivalent to the luminance of the color to be matched. The color specification is maintained by the X and Y coordinates. The XYZ color space serves mainly as an intermediate color space for the conversion from RGB space to the LAB color space described below.

The LAB cube-root color space was designed to provide a computationally simple measure of color in agreement with the Munsel color coordinate system (MacAdam 1942, Jain 1972, Munsel 1974, Faugeras 1979, and Robertson 1988). "L" is correlated with brightness, "A" with redness-greenness, and "B" with yellowness-blueness. The LAB color space provides a linear relationship between colors. The Euclidean distance between colors is directly proportional to the just noticeable color difference between the colors. The LAB color space is used for making color comparisons and color selection.

The CIPT was designed using the public domain X11 Windows Version 4 graphical interface. The X client was designed with the Open System's Foundation Motif toolkit. The use of the X11 windows for graphics permits the CIPT to run on any UNIX-based engineering and scientific workstation. The generic design of the CIPT and its portability to UNIX platforms makes the CIPT ideal for use in ER&WM programs for color image processing and inspection task.

The X11 window system shares one 256-entry color map among all client windows on a typical 8-bit display. This requires that the 24-bit color images be compressed to use the 8-bit display. The CIPT displays the 24-bit color images in an 8-bit pseudocolor window through the use of an Oak Ridge National Laboratory (ORNL) designed custom color selection algorithm. The algorithm searches the 512-by-512 color image, ensuring that the most used colors are included in the 256-entry color map. The color selection algorithm finds colors that are similar and have them share entries in the color map. If each color were different, this would mean that 256K colors have to be mapped into 256 colors in the color table. Because of the image content, many colors are essentially the same and can share the same color map entry with no observable image degradation. To ensure that no rust colors are thrown away, up to 50 of the color table entries are reserved for rust colors. Typically, the rust colors take up fewer than ten entries in the color table.

The algorithm uses an octree data base to record the colors used most in the image to be displayed (Schore 1991, and Probert 1991). The nodes in the octree are formed when the search color does not match any colors in the current color tree. The algorithm begins by comparing the search color with the color at the root node. If the color is within a given Euclidean distance of the current node, the color is considered to match. The color count at that node is then incremented. If the color does not match the color at the current node in the tree, the search continues on one of eight paths leading down the tree. The eight paths are based on the eight possible choices available to the search algorithm. The search algorithm is based on three variables: red, green, and blue. The results from a comparison of each of the variables result in two possible choices. The color component is either less than the node's color component, or it is greater than or equal to the node's component. The comparisons result in the eight choices shown in Table 2.

Table 2. Color comparison test results

	RED	GREEN	BLUE
0	>=	>=	>=
1	>=	>=	<
2	>=	<	>=
3	>=	<	<
4	<	>=	>=
5	<	>=	<
6	<	<	>=
7	<	<	<

The octree-structured database proved extremely useful in displaying the 24-bit RGB images on the X11 graphics display. The use of the algorithm prevented the need to purchase a 24-bit color display and graphics board. (The final system should use a 24-bit color display to speed up the display of color images and to ensure that the operator sees the images in as close as possible to the original form.)

SUMMARY

The rust inspection system uses color analysis to find rust spots in color images. The image acquisition system is composed of high-resolution color video equipment that permits the inspection of rust spots on the order of 0.254 cm (0.1 in.) in diameter. Because of the modular nature of the system design, the use of the VxWorks operating system, and the use of X11 graphics for the operator interface, the inspection system can be easily integrated into other ER&WM programs. The inspection system represents an excellent platform for the integration of other color inspection and color image processing algorithms.

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