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DEVELOPMENTS IN RADIOGRAPHY AND TOMOGRAPHY OF WASTE CONTAINERS AT THE IDAHO NATIONAL ENGINEERING LABORATORY

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ABSTRACT

The Idaho National Engineering Laboratory (INEL) has been inspecting containers (boxes and drums) of nuclear waste materials using real-time radiography (RTR) for the past ten years. In this time, requirements governing characterization of containerized waste for short-term storage, treatment, transportation, and disposal have become more stringent. These new requirements, and the need to reduce inspection times to increase throughput, necessitate improvements in the information obtained by radiographic methods. RTR provides a qualitative view of container contents, whereas quantitative information is often required. Additionally, it may be useful to combine quantitative information from radiographic/tomographic measurements of container contents and density estimates in digital form with other radioassay measurements and analyses performed on the same container. Although there is a need for advanced radiographic methods, the ability to acquire conventional analog RTR images for a qualitative "first look" will still be useful in waste container processing.

Two projects at the INEL are converting the present qualitative radiographic inspection to the more quantitative digital radiography (DR) and computed tomography (CT) methods, while retaining the RTR function. The first project is modifying the RTR hardware at the Radioactive Waste Management Complex (RWMC) to allow rapid processing of analog RTR images. The digital RTR (DRTR) system described here can digitize, process, and redisplay RTR images at video frame rates allowing for real-time image improvement features such as edge detection, contrast enhancement, frame subtraction, frame averaging, and a variety of digital filtering options. Additionally, DRTR allows online interactive image analysis for advanced image enhancement and quantitative volume estimation. The second project is developing a complete radiographic and tomographic capability that allows for greater sophistication in data acquisition and processing as the operator and/or requirements demand. The approach involves modification of an industrial CT scanner with the capability to acquire radiographic and tomographic data in several modes, including conventional RTR, DR, and CT with a linear detector for high spatial resolution, and DR and CT with an area detector for high throughput. Adaptation for high-throughput inspection of drums uses a large area scintillator coupled to, optionally, a conventional video camera or an integrating CCD camera. Selection of the various modes will be governed by the waste characterization requirements of the facility. Improvements in image quality and quantitative digital radiographic capabilities of the DRTR system are shown. Status and plans for the modified CT scanner (presently under development) are also presented.

I. INTRODUCTION

X-ray radiography and computed tomography share several imaging features. To obtain a complete image in radiography, or a portion of a tomographic imaging data set in CT, an object is irradiated by x-rays; the radiation that passes through the object is recorded on a detector. X-rays are either absorbed or scattered in the object of interest. The absorbed radiation obviously does not reach the detector, but a substantial portion of the scattered radiation might. Thus the detector responds to radiation that has either suffered no interaction with the object or has been scattered at least once. The radiation detected is a function of the x-ray absorption and scatter properties of the object as well as of the physical characteristics of the x-ray source and the x-ray intensity and energy distributions.

A conventional radiograph typically provides a 2D map of the x-ray intensity distribution arriving at the detector,

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which is a qualitative look at the 3D object volume, compressed onto the 2D map. The combined effects of x-ray scatter, x-ray absorption, and image compression are difficult to separate in a projection radiograph, and thus radiography remains a largely qualitative (but highly useful) tool. In real-time radiography, the x-ray intensity distribution at the detector is converted to a visible light image that an observer can view in real time. If the object is rotating, the observer perceives a three-dimensional picture of the object from a series of 2D projections. Typically, RTR systems provide output at video rates in video standard RS170 format so that each single projection making up the series of projections represents a 1/30 second x-ray exposure.

A digital radiograph is any digitally stored data set representing the x-ray intensity arriving at a detector. Digital radiographs can be obtained by digitizing the analog RTR data, or more directly by using a variety of x-ray sensors.

Computed tomography systems acquire a series of projection data sets, sampling the object at many projection angles. Since each of the projection data sets is a radiograph, CT data can be construed as a set of radiographs. Industrial CT systems typically rotate the object of interest, leaving the x-ray source and detector stationary, to acquire the multiple projection data. Each data point in the CT data set represents a summation of attenuation effects (absorption and scatter) along a line of sight from the x-ray source, through the object, and onto to the detector. The data are used to construct a map of the linear x-ray attenuation coefficient (μ) of the object. This coefficient is dependent on the elemental composition and electron density of the object, and on the energy distribution of the interrogating x-rays. A spatial map of μ yields combined elemental and density information about the object at each point. The CT data represent either a projection through a two-dimensional slice, yielding a one-dimensional data set, or a projection through a three-dimensional volume, yielding a two-dimensional data set (most similar to a single projection radiograph). A vast amount of literature from both the medical and industrial fields exists for CT (see References 1 and 2).

The Waste Isolation Pilot Plant (WIPP) Quality Assurance Program Plan requires the use of RTR for waste drum characterization. RTR is used to verify the Content Codes and the site-specific Item Description Codes of waste drums, to estimate the inventory of waste items within the drum or box, and to verify process knowledge. RTR is also used in a "semi-quantitative" mode to estimate volumes of free liquids and weights of materials when stored homogeneously in drums. These "semi-quantitative" estimates are achieved when an experienced operator makes an educated guess at volumes from a stationary image. The DR and CT techniques will improve the operator's ability to meet these requirements by providing true quantitative information and improved image quality. Other WIPP requirements for the assay of radioactive materials in drums may be better met when x-ray attenuation information is provided to other assay systems using active and passive neutron and gamma-ray measurements.

The RTR system used at the RWMC at the INEL is shown schematically in Figure 1. This system consists of a 420 kVp source, a gadolinium oxysulfide conversion screen, and an Isocon video camera to image the conversion screen. The RTR chamber can hold three 55-gallon drums, each of which can be rotated 360°. Additional degrees of freedom required for full examination of the drums are achieved by translating the source and detector synchronously in the vertical directions. The RTR system also has three different lenses on a turret that can be rotated remotely, providing the capability of magnifying the area of interest.

The next section describes the approach currently being used to enhance the RTR imaging capabilities by digital processing techniques prior to upgrades to the detector hardware. Section III then describes the status of the DR/CT project, plans for the immediate future, and possible implementations of a combined RTR/DR/CT system in the future. We close with some conclusions on the status and future of radiographic and tomographic methods for waste characterization.

II. DIGITAL REAL-TIME RADIOGRAPHIC PROCESSING SYSTEM

The objective of the DRTR approach is to provide RTR operators with more tools with which to evaluate the contents of waste containers and, where possible, to improve the overall image quality of the RTR images. The hardware used to achieve these goals and the current processing options are discussed below.

A. Digital Image Processing Hardware

The Imaging Technology (IT) Inc. digital image processing hardware used for the DRTR system is schematically shown in Figure 2. The image processing hardware resides in a VME chassis and is capable of processing video data at rates up to 40 MHz. Typical video signals are nominally 10 MHz, although very high resolution devices may have signals that are closer to the 40 MHz limit. The image processing hardware is controlled via an interface between a 66 MHz 486DX2 PC

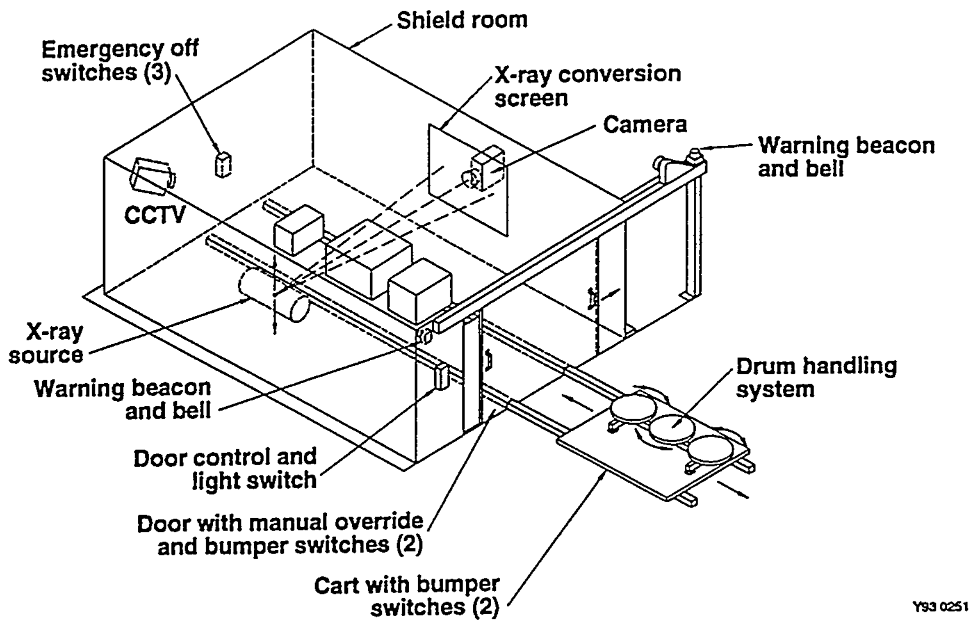


Figure 1. Schematic of the present RTR system for waste examination.

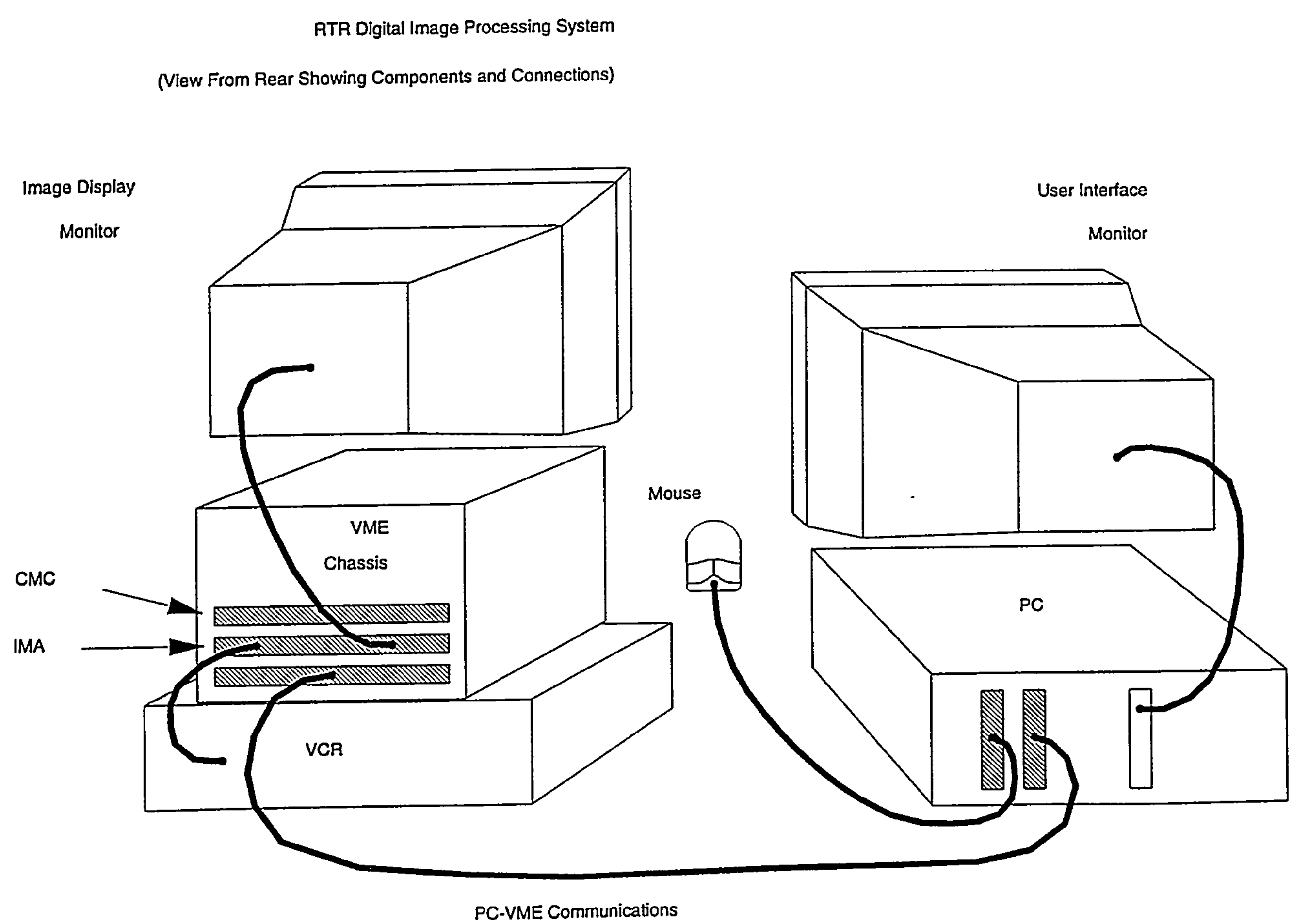


Figure 2. Schematic of the digital image processor used for the DRTR system.

and the VME chassis. Nearly all image processing operations are performed on the VME side of the interface and therefore processing rates are generally not limited by the PC or the PC-VME link. The hardware is accessed through C programs that contain hardware-specific function calls. The system is extremely modular--a variety of hardware modules are available to perform specific operations. For instance, one module contains an arithmetic and logic unit (ALU) as well as the circuitry to perform convolutions, while another module can perform nonlinear filtering such as median filtering. In addition, it is possible to chain several modules together in a sequence to perform very sophisticated processing in real time. The system currently in use contains an acquisition module for analog to digital conversion (A/D), a convolver/ALU module, a histogram/feature extractor module, a morphological (median filter) module, and a display module.

The acquisition module performs the A/D conversion of the incoming signal. This module also contains look-up tables (LUTs) that can be used to adjust the range and distribution of incoming pixel values based upon some functional relationship between pixel intensities coming into and going out of the LUT. An analog lowpass filter for noise suppression and the ability to adjust the A/D reference voltages are also contained on the acquisition module. By adjusting the reference voltages for the A/D conversion, the voltage range over which the digitization takes place is specified.

Standard linear filtering as well as ALU operations are possible using the convolver module. Linear filters convolve an n x m kernel with the image. Digital lowpass filtering (for noise reduction), highpass filtering (to accentuate high frequency components such as edges), and edge detection via first and second derivatives formed by the convolution kernel can be obtained using the convolver. The convolver unit also provides ALU operations such as addition and subtraction of two images, the addition or subtraction of constants, and logic operations such as *ANDing* or *ORing* of two images. Convolutions are performed to 32 bit (integer) precision using the convolver, followed by a scaling to 16 bits or 8 bits, depending upon user preference. The convolver module also contains two 8 bit input LUTs and one 16 bit output LUT.

Real-time histograms of images can be obtained using the histogram/feature extractor (HFE) module. A histogram indicates the number of pixels in the image at each gray level. This useful feature provides the necessary data for adjusting the contrast of images, providing the user with improved image quality. The HFE module also allows counting of features in an image, where a feature is a group of pixels with the same intensity value.

Various nonlinear operations are possible using the median and morphological processor computation module. This module provides useful real-time processing options such as median filtering, which is very effective for removing statistical noise from images. The filter operates by arranging the pixel values in a window (three windows are available: 3x3, 1x3, or 3x1) in ascending order and then choosing the pixel value in the median position as the value to use in a new image. This process removes outlying pixel values in the original image. The module also is capable of performing morphological operations such as dilation and erosion. Dilation increases high pixel value areas in an image, which helps to separate dark objects that are touching. Erosion has the opposite effect, and can help to separate high pixel value areas in an image by increasing low pixel value areas. The median/morphological computational module also contains an output LUT as well as an ALU.

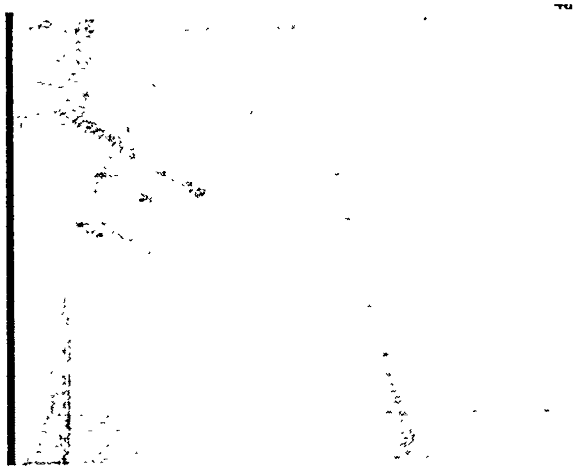
Processed images can be displayed either on a SVGA monitor or on a standard RGB monitor. The display module provides the capability of pseudocoloring output images via pseudocolor LUTs. Graphical overlays on the output images are also possible.

These descriptions of the modules in the digital image processing system are meant to give an overview of system capabilities--the description is by no means exhaustive.

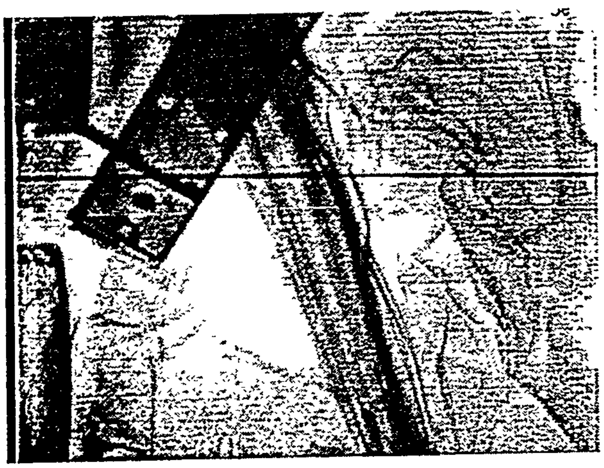
B. DRTR Processing Capabilities and Results

Numerous image processing and image analysis tools have been developed using the above described hardware.[3] Among these are real-time linear contrast stretching and histogram equalization of filtered and unfiltered RTR images, real-time frame subtraction for liquid detection, frame averaging to improve signal-to-noise ratio, and projected area measurement. Examples of linear contrast stretching and histogram equalization applied to RTR images can be seen in Figure 3. Both these processes can be performed on live RTR images using the LUT, which performs the desired contrast enhancement, updating at 15 Hz.

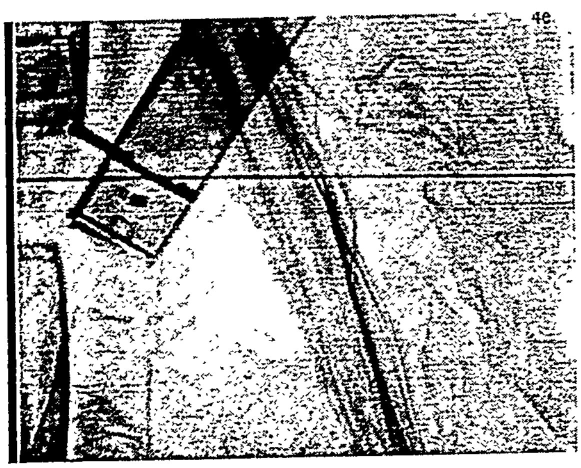
A second feature that has been developed is real-time convolution. The current image format is 640 x 480 pixels, or roughly 300,000 pixels. The significance of this number is that a new image obtained with a single 3 x 3 convolution is the result of approximately 2.7 million multiplications. In real-time processing this occurs 30 times per second, indicating that the processing rate is nominally 81 million multiplications per second. Typical uses of convolution are highpass and lowpass filtering and first and second derivatives to detect edges in an image.



a. Original image.



b. Enhanced by nonlinear, histogram equalization.



c. Enhanced by linear contrast stretch.

Figure 3. Contrast enhancement of RTR images.

Figure 4 shows the results of Sobel magnitude edge detection on an RTR image; note that the edges of the snaps on anti-C clothing at the image center, as well as of a variety of other objects, have been enhanced. To perform this edge detection, two convolutions of the original image must be performed. The two kernels used take the derivatives of the image in the north-south and east-west directions, then the absolute values of the resultant images are summed, resulting in the image shown in Figure 4b. This operation, performed with 3 x 3 kernels, is easily accomplished at video data rates (i.e., more than 180 million computations per second).

The digital image processing system currently supports real-time processing with kernel dimensions up to 4 x 4. In the near future, the real-time kernel dimension will increase to as much as 8 x 8. In addition to performing the above convolutions (any 3 x 3 or 4 x 4 kernel can be used), single kernel operations can be chained with the previously described contrast enhancement schemes to provide an image of improved visual quality in real-time. For instance, a highpass filter can be used to bring out edges in

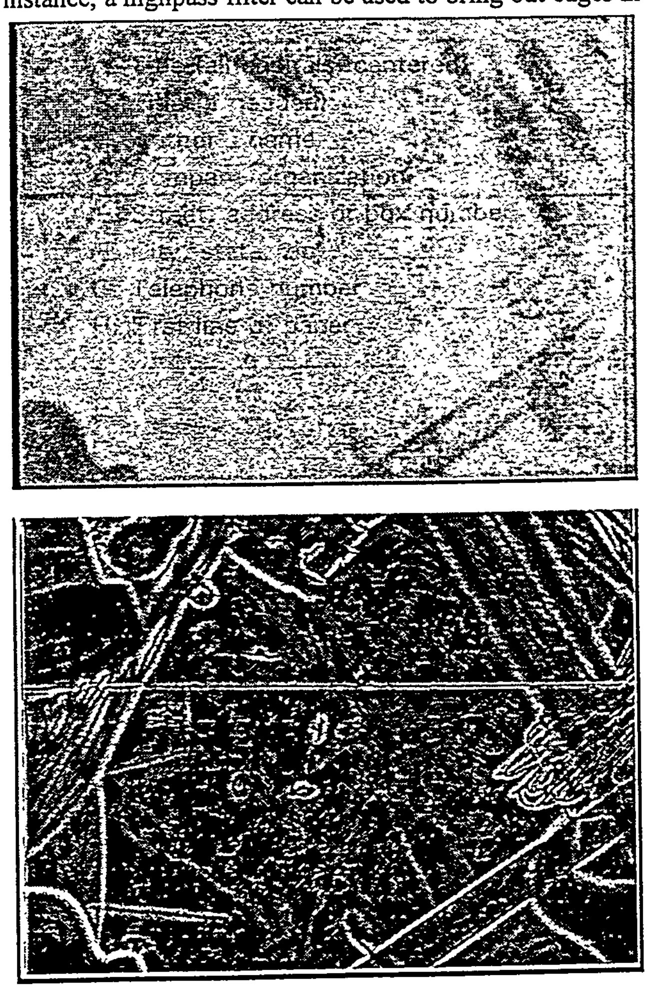


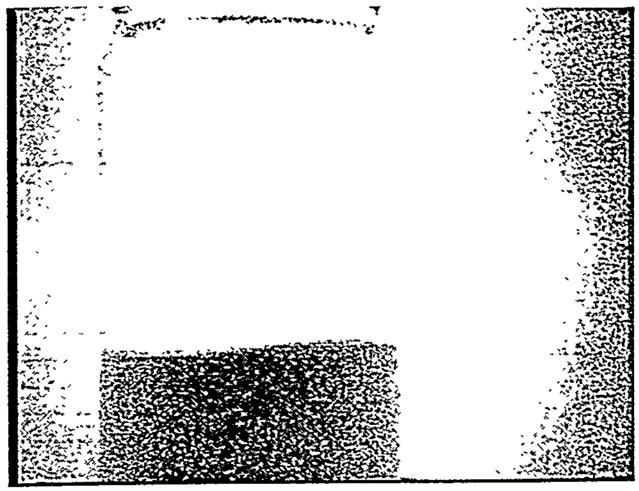
Figure 4. Sobel edge enhancement on an RTR image.

an image in conjunction with linear contrast stretching and median filtering, providing the user with a powerful tool for qualitative image analysis.

Digital image processing provides a convenient means to determine free-liquid volumes. The image processing hardware allows real-time subtraction of temporally adjacent live images so that the output shows only the difference from one frame to the next. Thus, if the liquid is moving, the output image will show where liquid is present--the rest of the image will be zero since no movement is occurring. The operators jiggle the drums, using the drum stage's motorized translation capability, to see if there are any visual indications of liquid motion. Real-time frame subtraction will enhance this process. Figure 5b shows the results of such a subtraction; the black areas indicate liquid motion. This liquid detection feature is the first step in what could eventually be a fully automated liquid detection and quantification algorithm.

The ability to quantify free-liquid volumes is being developed. A first step in this process is to determine the projected area of the volume of interest. Figure 6a shows an RTR image of a drum containing a paint can. For this standard size can, the volume of liquid is found by determining the void volume and subtracting it from the can's known capacity. In Figure 6b the projection of the can's void region onto the conversion screen is highlighted using a dark overlay. The projected area is identified by outlining it using the mouse-controlled cursor of the image processing system. Figure 6c shows the same paint can after rotating the drum by 90°; the projection of the void region is highlighted in Figure 6d. With these two areas known, and with the geometry of the source and detector known, an estimate of the volume of the void region can be computed. The projected areas are backprojected to the x-ray source. The volume of the region where the backprojections intersect is the estimated volume of the void region of the paint can. This estimate represents an upper bound to the actual volume of the void space in the can. The use of a larger number of drum orientations would improve the accuracy of the estimate, but at the expense of a considerable increase in computational complexity.

The DRTR processing system with the features previously discussed is nearly ready for use. A graphical user interface (GUI) is under development to allow convenient access to the algorithms. The system will be tested at RWMC and the features most useful to operations personnel will be incorporated into the GUI.



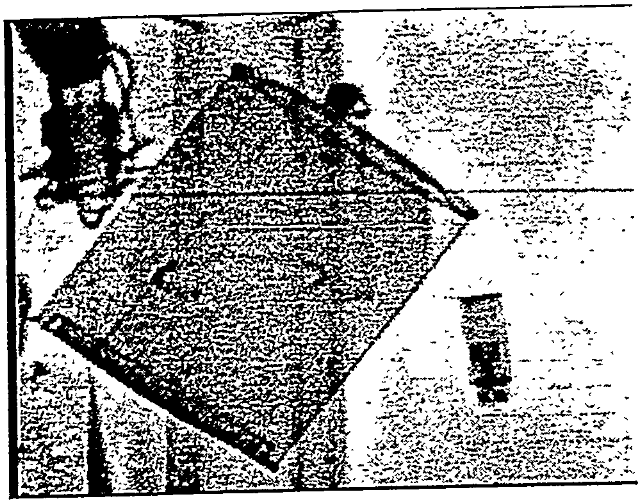
a. Radiograph of a container with liquid in motion.

b. Liquid in motion (black areas) revealed by subtracting two adjacent incoming images and thresholding the result.

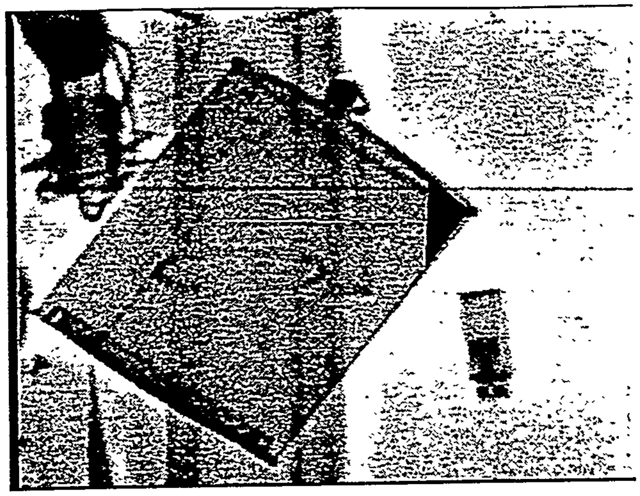
Figure 5. Liquid detection by frame subtraction.

III. DIGITAL RADIOGRAPHY AND COMPUTED TOMOGRAPHY SYSTEM

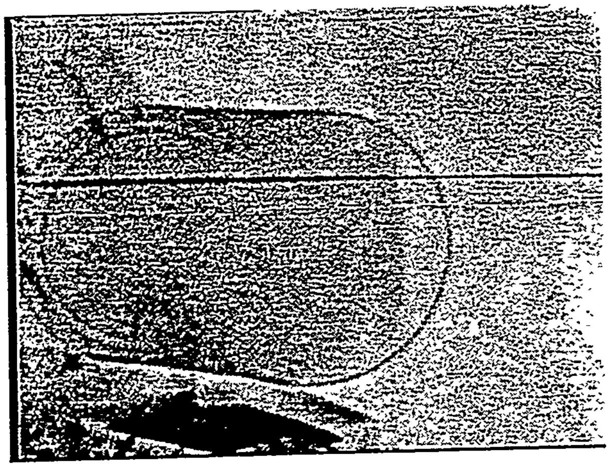
An industrial CT scanner originally manufactured by Scientific Measurement Systems (SMS), Inc. and sold to another government agency was acquired late in 1992; it has been refurbished and upgraded over the last several months by SMS. This SMS Model 201 CITA™ is a digital radiography and computed tomography scanner, functional with either x-ray or gamma ray sources, containing a linear detector array consisting of 125 individual plastic scintillators coupled to photomultiplier tubes. Currently, a 420 kVp x-ray source is used. Two-dimensional radiographs are obtained by vertically scanning a specimen with the linear array and x-ray source, synchronized in motion, to acquire a series of linear projections. Transaxial



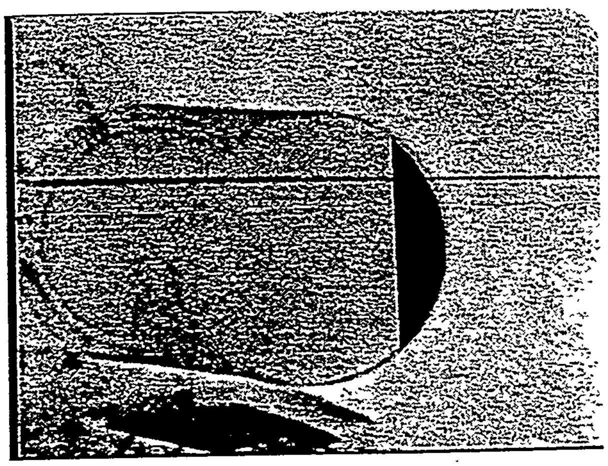
a. Radiograph of paint can.



b. Projection of the void region, highlighted with dark overlay.



c. Paint can after 90° rotation (about horizontal axis of figure).



d. Projection of void region, highlighted.

Figure 6. Quantification of free-liquid volume.

or single slice CT data sets are acquired as either second generation (translate and rotate) or third generation (rotate only); a full 3D data set is acquired by vertically scanning the x-ray source and detector array and repeating the transaxial measurements at each vertical position.

The system now comprises a combination of original and upgraded components. Presently, motion control and data acquisition are achieved with the original computing equipment from Digital Equipment Corporation, while reconstruction and data processing are performed on a SUN SPARC 10 workstation. The system is undergoing an additional upgrade to allow it to function in both RTR and 3D CT data acquisition modes. A large area x-ray scintillator will be installed and the visible light output from the scintillator will be optically imaged onto either a video rate CCD camera or an integrating (slow scan) CCD camera. The experimental version of this detector will allow for a continuously variable field of view up to the full size of a 55-gallon drum. A full-size drum RTR experiment was recently performed by the Computed Tomography Group at Lawrence Livermore National Laboratory.[4,5]

The refurbished scanner was put through a series of performance tests to verify system specifications and to determine its capabilities with respect to imaging 55-gallon drums. The system exhibited greater than 50% contrast at 1 linepair/mm (0.5 mm spatial resolution) on a linepair phantom in air and comparable contrast at 2 mm spatial resolution on a linepair phantom entrenched in a lucite disk 54.6 cm (21.5 in.) in diameter (Figure 7). The lucite disk fits snugly inside the liner of a 55-gallon drum. Full-size (55-gallon) calibration drums designed and constructed at INEL were also scanned. A CT reconstruction of a horizontal slice through a drum containing graphite bricks

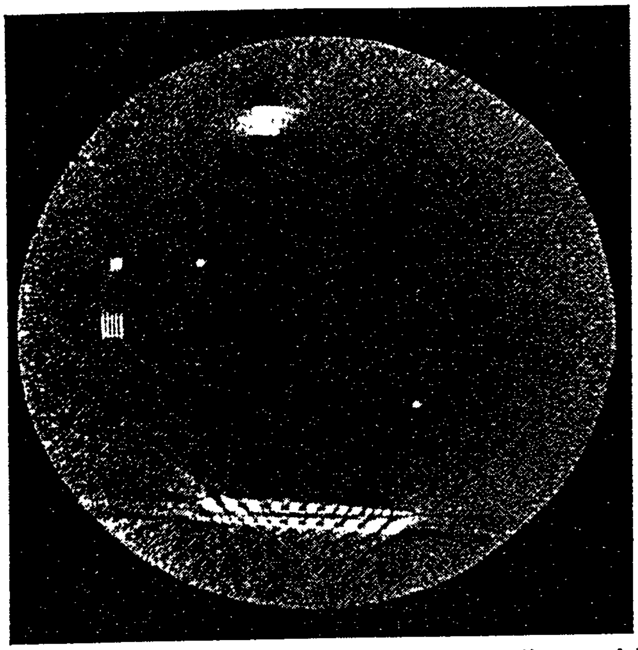


Figure 7. CT reconstruction of a single-slice spatial resolution phantom. The objects of interest within the lucite disk are a 5x5 array of 2 mm diameter stainless steel cylinders separated by 4 mm (center to center), and two linear arrays of cylinders (3 each of 1.0, 0.8, 0.6, 0.4, 0.2, and 0.1 mm; the last are not visible).

is shown in Figure 8. The image shows the bricks with holes and three hollow cylinders with clips to hold isotopic sources (no sources were in the drum during this scan). The central cylinder contains a 2 mm diameter steel ball bearing used to emulate a high density object such as plutonium. The image indicates the capability of CT to spatially locate high-density radioisotopes within a drum. Data acquisition time for this scan was about 40 minutes, indicating the need for improved throughput with comparable spatial resolution.

The scanner is due to be installed in Idaho in late July, 1994. It will initially be installed on the campus of Idaho State University while undergoing tests for optimum configuration of the large area detector. High-energy imaging with a 2 MeV linac will also be explored. The system will be installed at INEL late in FY-95 or FY-96, where it may serve a dual role as an experimental tool and a production scanner for waste drum characterization.

SUMMARY AND CONCLUSIONS

Improvements to existing radiography systems at INEL and other DOE sites are necessary to meet evolving requirements for the characterization of containers of

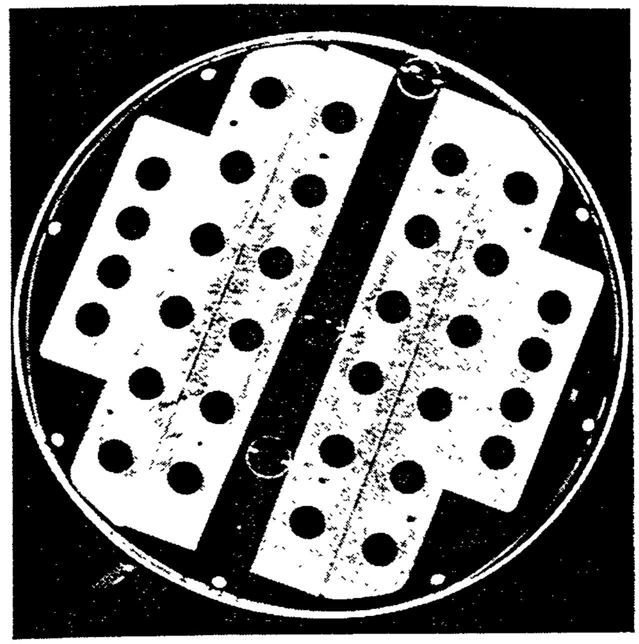


Figure 8. CT slice of graphite calibration drum showing stainless steel ball bearings in source tubes.

nuclear waste. While RTR has proven invaluable for qualitative "first looks" at containerized waste, improved qualitative and quantitative information can be gained by digitally capturing and processing the analog images from RTR. A digital image processing system has been developed that provides RTR operators with improved image quality and interactive tools for quantitative image analysis. The system provides for a wide variety of digital filtering operations, contrast enhancement, volume estimation, and liquid detection and estimation. The DRTR processing system is applicable to a variety of hardware x-ray detection schemes. The DRCT scanner, when modifications are complete, will allow for a suite of radiographic and tomographic measurements to be made, including RTR, DR, transaxial CT, and 3D CT, at either high spatial resolution or high throughput. Digital radiographic and tomographic capability will allow much more accurate quantitative estimates of liquid volumes and material masses. The information from CT will enable refinements in data analysis of quantitative assay measurements.

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