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CC: J.P. Howell, 773-A
N.G. Awadalla, 773-41A
M.J. Green, 235-H
D.L. Hayes, 235-H
M.R. Louthan, 773-41A
M.J. Morgan, 773-A
D.H. Wheeler, 773-A
J.E. Marra, 773-A
D.T. Rankin, 773-41A
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C.L. Angerman, 773-A
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W.R. Kanne, Jr., 773-42A
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MEMORANDUM

To: J.M. Stone, 773-41A

From: E.A. Clark, 773-A

SURVEY OF DIGITAL IMAGING TECHNOLOGY AND APPLICATIONS AT THE SAVANNAH RIVER SITE (U)

Derivative Classifier: J.P. Howell

Summary

An introduction to methods of digital image analysis is presented. Modern commercially available digital image analysis systems are described, along with applications that may be useful to programs at the Savannah River Site (SRS). Systems to aid inspection of tritium reservoir fill stems and a system to enhance inspection of radiographs of pinch weld closures of tritium reservoirs have already been developed at SRS. Modern digital analysis systems based on personal computers have been and are being procured for use in SRL programs, and are finding immediate application in several programs requiring quantitative metallography. It is argued that x-ray computed tomographic imaging, digitally-enhanced ultrasonic testing and acoustic microscopy are three techniques that would enhance not only the research and development efforts at SRL, but also may be applicable in production (for example, in pinch and reclamation welding of tritium reservoirs, and in reactor component inspection) as quality assurance and documentation tools.

Introduction

Digital imaging technology refers both to the conversion of an image to a set of numbers which uniquely describes the image, and to the numerical operations on this set of numbers that allow additional information about the image to be obtained. The word "image" here refers to any type of image forming technology. For example, images can come from any type of photograph, television and movies, micrographs from optical microscopes or scanning and transmission electron microscopes, thermal image detectors[1], acoustic microscopes, or computed tomography (using x-rays, nuclear magnetic resonance, or ultrasound). Virtually any physical property that can be measured locally can be used to form an image.

In many cases, modern personal computers suffice for basic image analysis[2]. The conversion of images to numerical form is easily accomplished using a "frame grabber" and appropriate software in a computer. Frame grabbers are now readily available that are small enough to be expansion boards compatible with common types of personal computers. Current image analysis systems are generally sold as a complete package ready for use (including video camera, computer with required image expansion boards, software, and image storage and output devices), so that users generally need only to specify the requirements for the system to be used. Systems are also made that use specialized computers, hardware and software designed to handle the enormous amount of data that specialized image analysis techniques may require (for example, the various forms of computed tomography, discussed below).

Images are stored in computer memory as follows. A discrete two dimensional coordinate system is defined that describes the plane of the image, and for each position in the image (termed a "pixel"), another number from a discrete scale called the "grey scale" defines the intensity of the image at that position. In the case of true color systems, three grey scale numbers (corresponding to the three primary colors) is specified for each pixel. A typical modern image system has 512 by 512 or 262144 pixels per image, and each pixel has one of 256 grey levels. The function of the frame grabber is to convert the image to this digital representation. An additional feature of modern systems is "pseudo-coloring", or assigning different colors on an output video terminal to different ranges of the grey scale. This feature is used in aiding the operator in defining and observing the different grey levels used in quantitative metallography (discussed below); pseudo-color can be an aid in image interpretation and an enhancement of image quality as well.

Some Specific Techniques of Digital Image Analysis

Three general areas of digital image analysis or processing are: image enhancement, quantitative image analysis, and computed tomography. Image enhancement involves numerical filtering of the image data to alter contrast, remove noise, or subtract either background or a previous image to observe differences in the image area. Once the image is digitally stored in computer memory as discussed above, these enhancement functions are relatively easily implemented. For example, an algorithm to reduce contrast would assign a new grey level to a pixel that is the weighted average of the old grey level at the same pixel and the eight pixels around it. To increase contrast, the difference in grey scale value between adjacent pixels can be multiplied by a non-linear function. Noise reduction can be done by expressing the grey scale as a Fourier transform and rejecting high-frequency components. Although easily implemented, the theory of algorithms in image enhancement is quite complicated and continues to be a subject of ongoing research[3]. Image subtraction is more straightforward: the grey level at equivalent pixels of two images are subtracted, and then scaled if necessary so that the resulting grey levels in the difference image fall in the range of allowable grey levels the system requires for display (typically between 0 and 255).

Quantitative image analysis is the computation of average properties of features of an image through numerical techniques[4]. Quantitative metallography and stereology are ideally suited for implementation in a digital image analysis system[5]. By defining grey scale ranges that correspond to different image features (for example, to grain boundaries and grain interiors) the image system software can simply count the number of pixels in each feature (the grains in a micrograph of a polished and etched sample) and derive average feature sizes (grain sizes), count the features, and derive mathematical measures of feature shapes. Any number of feature types in one image can be analyzed in this way, if each has a unique grey scale range. The use of pseudo-colors discussed above is ideal for representing different grey-scale ranges on the video screen during analysis. If unique grey scale ranges cannot be assigned to differing image features but the system operator knows from experience which features should be grouped together (for example, grain boundaries, second phase particles, and grain interiors above), modern systems allow the operator to group features by "drawing in" each feature type (typically with a computer "mouse"); although more time consuming, quantitative image analysis can then proceed even without a unique relationship between grey scale range and feature type. It is important to keep in mind that this quantitative techniques are applicable in a wide variety of fields, from biology[6] to materials science[5] because the only requirement of quantitative analysis of features is the unique correspondence of grey scale with feature type.

Computed tomography (CT) is a somewhat specialized type of digital image analysis[7]. It is the synthesis by computer of two-dimensional images of cross sections of three-dimensional bodies from experimental information about the body obtained from many different directions. X-ray CT, nuclear magnetic resonance imaging, and ultrasonic CT are all examples of computed tomography used in medicine. X-ray CT involves measuring the attenuation of intensity of x-rays transmitted through a solid (be it a human patient or a solid part). It is essentially an advanced form of radiography, but instead of using only one projection, cross sectional images are synthesized from radiography data from many x-ray beam directions. Examples of x-ray CT use are: study of thermal damage of nuclear fuel rods[8] and inspection of ceramic turbine components[9].

Ultrasonic CT utilizes ultrasonic elastic waves instead of x-rays[7]. It is a broader technique than x-ray CT in the sense that both transmission and reflection of sound waves can be monitored. Measurements of either ultrasonic attenuation or of sound velocity and echo in a part are used to synthesize images of interior cross-sections. This technique is sensitive to differences in elastic properties inside solids, and has the potential to have higher sensitivity to directionally varying properties than it's x-ray counterpart because of this. Ultrasonic CT can be more difficult to interpret than x-ray CT, however, because diffraction of sound waves often occurs and makes the analysis even more complicated.

Digital image enhancement of conventional ultrasonic testing has been used to detect impact flaws and delamination in composite forms[10]. Frock and Martin describe how various digital image analysis techniques can be used with ultrasonic testing data; they studied cure cracks in a graphite-epoxy resin[11].

Another technique related to digital image analysis is scanning acoustic microscopy[12]. A focused sound wave, at a frequency between about 500 MHz and 2 GHz[13], is created by a suitably designed transducer and is directed through a thin film of water toward a sample having a polished surface. The sound waves interact with the sample and reflected waves are detected. By scanning in two dimensions, and using an image analysis system incorporated in the microscope, an image is made which reflects elastic property changes in the material at the surface and in the bulk. Grain structure and second phase particles are easily observed in solids without etching[14]. In favorable cases, information from under the surface can be observed and is used, for example, in evaluating bonding of semiconductor components[15]. Similar to a C-scan in ultrasonic testing of materials, acoustic microscopy offers much better resolution in the plane of the sample surface than C-scan ultrasonic testing while sacrificing some ability to measure in depth. At 2 GHz, the surface resolution can be 0.65 µm with a penetration depth of 3 µm, while at 0.1MHz, the resolution is 15 µm and a penetration depth of 800 µm (0.024")[13].

Applications using Digital Image Analysis at SRS

An excellent example of the usefulness of digital image analysis is the Unwrap System, a true-color borescope/video system developed by W.C. Mosley and co-workers at the Savannah River Laboratory (SRL)[16]. Currently, human operators inspect the interior of tritium reservoir fill stems for cleanliness before loading using an optical borescope. Possible differences in subjective judgment of cleanliness between operators made it desireable to develop an image analysis capability less dependent on the operator and having the ability to record the image permanently. The Unwrap System controls the motion of the borescope down the stem, records the transmitted visual image, and then performs a transformation of the digitized image, converting it to a planar form which is much easier to inspect. Also, the system separates the image into the three primary colors, which may be useful in analyzing different kinds of contamination in unclean fill stems.

Pinch welding is a solid-state resistance bond technique used as the final closure of the fill stems of tritium reservoirs at SRS. A digital image analysis system has been developed by a group led by D. Hayes to improve the quality and efficiency of post-pinch weld radiographic inspection[17]. Pseudo-coloring and grey-level averaging enables rapid unambiguous measurement of the pinch weld bond length to +/- 0.001 inch, compared to the earlier method of +/- 0.0025 inch which is subject to human interpretation. Other geometrical features of the weld present in the radiograph can be quantified as well, such as extrusion length and base, minimum wall thickness, and open bore dimension. These data are stored and can be used in long-term studies of trends in production welds.

J. Marra is using a modern commercially available digital image analysis system at SRS to study the morphology and porosity of $Pu^{238}O_2$ powder compacts[18]. The grey scales are defined to measure area fraction of powder and pores. Also, the grain size and other microstructural features of the powder are being investigated. This system is useful for many types of quantitative metallography as well as image enhancement. A similar use of digital image analysis of dynamically compacted aluminum powder is described by Morimoto et al[19].

Suggested New Applications of Digital Image Technology at SRS

A modern digital image analysis system (having many of the features discussed above) is being purchased and will be available for general use by SRL personnel. This system will be able to perform many ASTM quantitative metallography measurements. The measurement of grain size variations (using images from both optical metallography and scanning and transmission electron microscopy) in High-Energy-Rate-Forged (HERFed) materials will further understanding of mechanical properties and tritium compatibility effects in these materials. As the system becomes familiar to the operators, it's use in day-to-day microstructural investigations in other programs will increase.

X-ray CT, digital-image-enhanced ultrasonic testing, and acoustic microscopy should be evaluated as candidates for inspection of pinch welds of tritium reservoir fill stems. Since the pinch weld is the final closure done on production reservoirs, non-destructive post-weld evaluation is especially important in this weld. Work has been done at Sandia National Laboratory in Livermore, CA to determine the feasibility of ultrasonic testing and of acoustic microscopy in the evaluation of pinch welds[20]. Using digital feature extraction and pattern recognition techniques, the authors report the ability to distinguish between good and bad welds. They also report acoustic microscope images that revealed differences in pre-weld cleanliness. In addition, both digital-image-enhanced ultrasonic testing and acoustic microscopy should be evaluated as an overall enhancement of non-destructive evaluation capability of plant facilities. In addition, acoustic microscopy and x-ray CT would be valuable additions to the microstructural analysis capability of SRL and would both find use in many programs both in Materials Technology and in the whole site. Current efforts in the Alternate Repair Technology program may profit from acoustic microscopy observations of simulated low-energy-input welds on helium-containing 304L stainless. Commercial acoustic microscopes cost about $300M.

X-ray CT should be evaluated as an inspection tool for reclamation welds (another solid state weld technique used at SRS). Misalignment of the new stem in the reclaimed reservoir can cause uneven heating during welding which can lead to an uneven or poor quality weld. X-ray tomography may allow images to be made of the interior near the base of the stem and thus enable direct study and evaluation of reclamation welding procedures. These images may have the resolution to detect flaws and cracks as well as the form of the stem bottom in the reservoir. Travel to Weapons Complex sites having x-ray CT systems would aid in establishing the usefulness of the technique at SRS; Many of the other sites have x-ray CT systems which have been designed and built by Sandia National Laboratories- Albuquerque[21]. They are used in various applications in analysis of parts and materials. At a cost of about $100M, these systems are significantly less expensive than typical commercially available systems, which cost approximately $1MM. Ultrasonic CT is a more specialized technique, and evaluation for it's use at SRS would not be worthwhile at this time.

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