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The State of the Art of Weld Seam Radiographic Testing: Part I, Image Processing

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ABSTRACT

Over the past 30 years, a large amount of research has been conducted to develop an automatic (or semiautomatic) system for the radiographic detection and classification of discontinuities in continuous welds. There are two major types of research in this field: image processing, which consists of improving radiographic image quality and segmenting regions of interest in the images, and pattern recognition, which aims at detecting and classifying the discontinuities segmented in the images. Because of the complexity of the problem of detecting weld discontinuities, a large number of techniques have been investigated in these areas. This paper represents a state of the art report on weld testing and is divided into separate parts on image processing and pattern recognition. The techniques presented are compared at each basic step of system development for the identification of discontinuities in continuous welds. This part deals with image processing.
Keywords: *weld discontinuities, nondestructive testing, radiography, automatic weld testing, image analysis.*

INTRODUCTION

The first experiments in detecting weld discontinuities using X-rays took place on the laboratory scale at Yale University in 1896, barely one year after the discovery of X-rays by Wilhelm Conrad Röntgen in Germany (Richter, 1999). However, it was in 1927 that the first industrial X-ray equipment was developed to carry out these tests on a larger scale. After obtaining the radiograph, the test is done by visual interpretation of the X-ray image, which shows radiation energy attenuation as it goes through the object being studied. Testing by X-rays became so important that in 1930 the American Society of Mechanical Engineering (ASME) accepted its use for weld quality control in steam boilers. During the Second World War, it was used extensively for the testing of ships, submarines and airplanes. It is estimated in 1954 that about 50% of all welds in West German steel construction were tested using X-rays. Even though it is true that in the 1960s there was clarity in relation to quality control programs for welds (McGonnagle, 1965), it was only in 1975 that a weld radiograph was digitized for the first time, and that meant the beginning of automatic visual testing of welds based on digital image processing techniques. (It should be mentioned that Shirai [1969] studies algorithms for weld testing, but his methodology made use of photographs for superficial testing, and not radiographs to investigate the inside of the weld.) Nowadays, industrial radiography of welds is widely used for the detection of discontinuities in the petroleum, chemical, nuclear, naval, aeronautics and civil construction industries, among others.

The success of weld testing depends strictly on the quality of the X-ray image, which varies as a function of multiple testing parameters such as the focus to film distance, focus size, film to object distance, use of image intensifying screens, filters, test geometry, exposure time, film type, and chemical film processing, among others (Halmshaw, 1995). Visual testing of weld discontinuities is an extremely difficult task, as reported in the first paper on the subject in 1936 (Richter, 1999). Conventional interpretation of radiographic films performed by qualified inspectors certified for that task is highly subjective and is subject to errors, in addition to being a slow and expensive process (Fucsok and Scharmach, 2000; Fucsok et al., 2002). To minimize this problem, numerous investigations on automatic weld testing were conducted making use of the development of computers and digital image processing and pattern recognition techniques, and of image digitization devices such as charge coupled device (CCD) cameras (Castleman, 1996; Davis, 2005), and much work was done trying to develop techniques that could optimize the radiographic aspect in terms of precision, time and cost.

At present, much research is being done trying to develop an automatic (or semiautomatic) system for the detection and classification of continuous weld discontinuities examined by X-rays. (Radiographic weld testing has become so important that institutions like ASNT and DGZfP organize conferences devoted solely to this area of research.) However, it is pertinent to ask what the state of the art of research in this subject is. The present paper makes a brief and objective description of the state of the art in automatic testing of weld seams by digital radiography based on the publications that have appeared over the last decades, comparing the various techniques that are used and pointing out the possible trends in the development of this research over the coming years. The paper, divided into separate parts on image processing and pattern recognition, follows the outline shown in Figures 1 and 2, consisting of three stages: image acquisition; preprocessing, segmentation, feature extraction and detection of discontinuities; and classification of the discontinuities found. The first and second stages are covered in Part I, while the third will be discussed in Part II. Each stage will be taken up separately, and a table will appear in Part II showing the main technical aspects and results obtained by each author. As will be seen in this paper, automatic detection of weld discontinuities is still an unresolved research field, since there is a large variety of situations in which the discontinuities cannot yet be recognized by computational algorithms.

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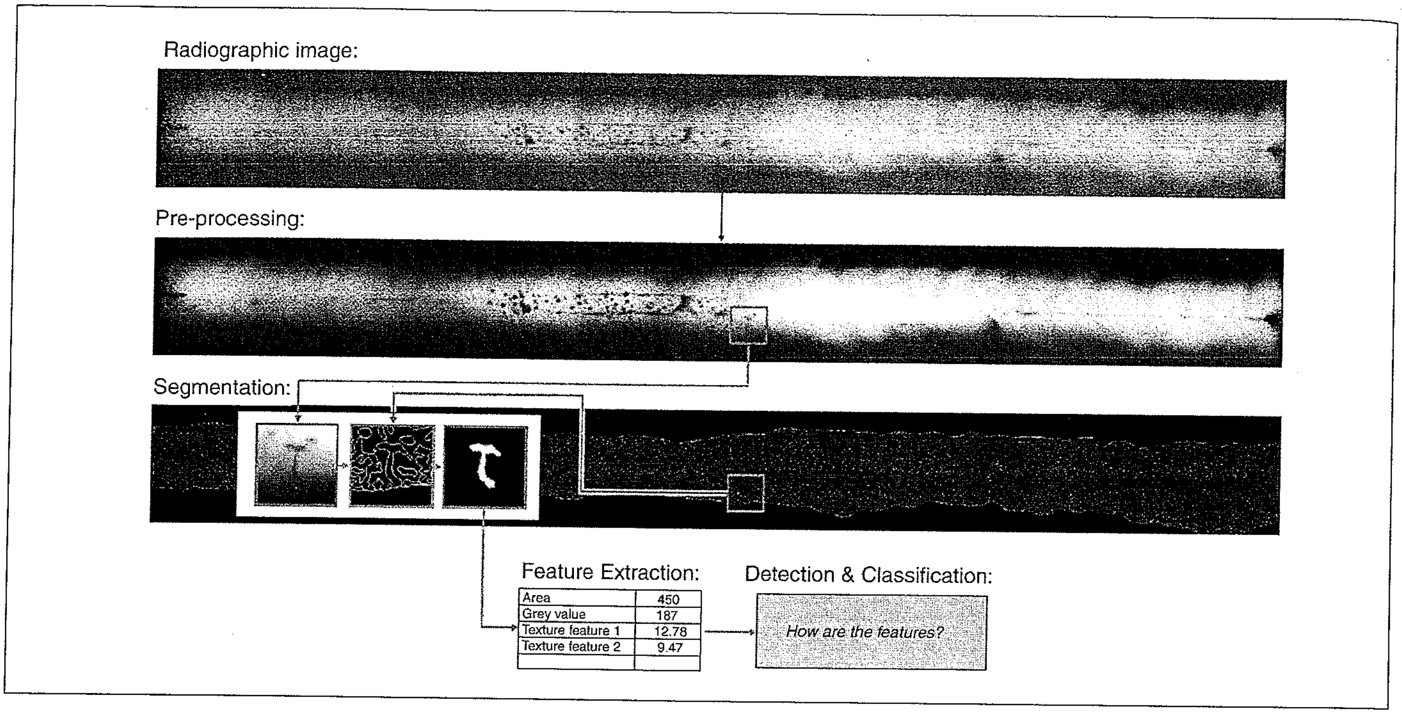

Figure 1 — Schematic diagram of the detection of discontinuities in welds.

RADIOGRAPHIC IMAGE ACQUISITION

A digitization process is normally divided into two stages: the sampling stage, in which its spatial resolution is defined, and the quantization stage, in which the resolution of the gray tones of the image is defined. These two stages are very important because they determine the level of information that the image will contain after being digitized (Castleman, 1996; Davis, 2005; Gonzalez and Woods, 1992). There are some techniques for digitizing radiographs that will be described briefly below.

Photography with CCD Cameras

Charge coupled devices are the most widely used equipment for image digitization. Initially, X-ray films were digitized by placing them on a lightbox and photographing them with a CCD camera (Aoki and Suga, 1997; Aoki and Suga, 1999; Murakami, 1998; Suga et al., 1995). In this process, the energy of the photons captured by the camera is converted into voltage for each image pixel; the number of pixels is determined from spatial resolution. Then, each voltage of the pixels corresponds to a gray level (gray level resolution). Then the digitized radiographic images are transferred to the computer to be processed digitally with the purpose of removing noise, improving contrast and segmentation.

Suga et al. (1995) describe the process of obtaining high contrast images during digitization using a CCD camera. These radiograph digitization processes have already become outdated and are generally no longer used because the spatial and gray level resolutions are usually inferior when compared with those obtained by more modern techniques (such as those described in the following sections). However, Shafeek et al. (2004a; 2004b) have used the technique described by Suga et al. (1995) with good results.

Digitization of X-ray Films through Their Appropriate Scanners

There are currently several types of radiograph digitization scanners that operate in the light transmission mode. In this case, the films are placed in the digitizing area, which can be of the flatbed type (similar to conventional scanners), and the light coming from the transparency adaptor goes through the image; that light is normally captured by a CCD in the bottom part of the scanner. The resolution and density limits of the apparatus, as well as the capture driver, define the characteristics of the digitized radiographic image (there are now scanners capable of digitizing films with optical densities up to 4.0). There are also scanners that use laser beams as light sources, allowing a much greater concentration of photons, and therefore greater precision for digitizing high density films.

Cherfa et al. (1998), Li and Liao (1996) and Silva et al. (2001) used scanners in their work to digitize radiographs. Li and Liao (1996) and Wang and Liao (2002) used a scanner that allowed a spatial resolution of 70 μm pixels, each pixel having 12 bits (4096 levels of gray).

The improvement in image quality obtained with this technique compared to that of the lightbox camera set is evident because of the better resolution achieved and the resources available with the scanners.

Digitization of Phosphor Plates

In addition to film digitization, there is the digitization of plates containing crystals of photostimulated phosphor, which, when exposed to X-rays or gamma rays, result in some of the electrons going to a higher, semistable energy state. Using a beam of rays, these electrons return to the stable energy state and emit visible light that is captured and converted into a digital radiographic image. The digitized plates can be erased and reused in new exposures, in contrast to what happens with films, leading to economy in the radiographic testing process as well as to greater speed in the process of image visualization (Blakeley, 2004).

IMAGE PROCESSING

The quality of radiographic images is an important factor in the detection of weld discontinuities, and it is normally evaluated through the use of image quality indicators (Castleman, 1996). Factors such as film type, film density, focus to film distance, energy level of the source, exposure time, and developer temperature are controlled so that an image is obtained with satisfactory quality so that it can be useful for the correct detection and classification of discontinuities (Castleman, 1996).

Even when the parameters of the radiographic test are chosen carefully, the images present problems such as the existence of noise, nonuniform distribution of grays, and deficient contrast. In this way, when there is a very small discontinuity in the weld bead, it can be confused with noise existing in the image, whether it originates in the digitization stage or even in the process of testing (McGonnagle, 1965).

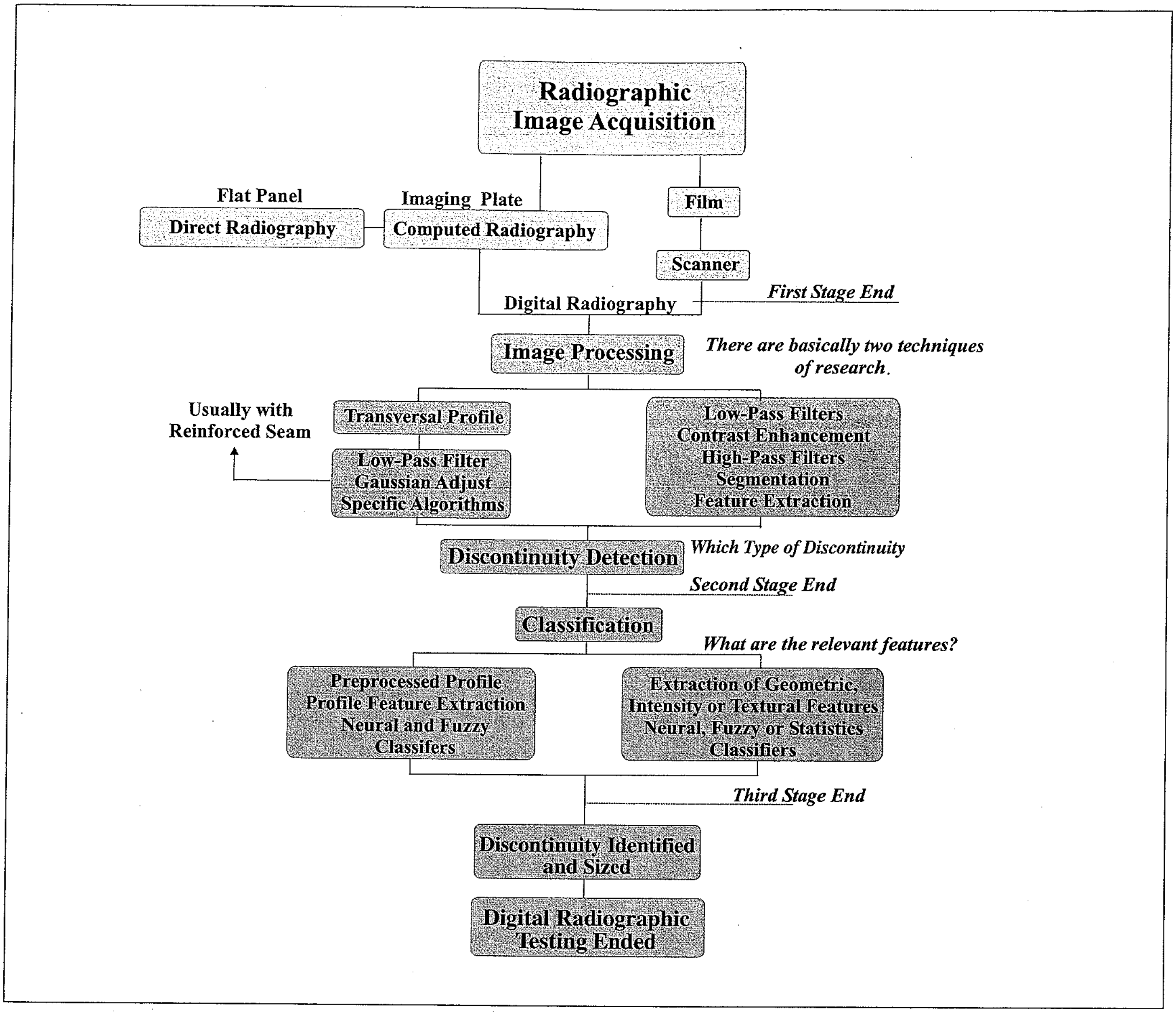

Figure 2 — Stages of automatic testing of weld seams by digital radiography.

After digitizing the images, there is the possibility of processing them with the application of digital image filters, eliminating or smoothing such problems. It should be mentioned that the application of the filters must be made carefully so that no relevant information is lost, which could generate the underrating of a discontinuity or even its exclusion from the image.

As will be shown, the processing stage of industrial radiography is quite complex, and the diversification of the techniques used is verified in various articles mentioned throughout this paper.

Smoothing Noise with Low-pass Filters

The first stage in image processing is smoothing noise that can have its origin either in the testing technique (McGonnalge, 1965) or in the digitization process (the latter being known as electronic noise). In this stage, low-pass filters are normally applied, since noise is characterized by high frequencies (Castleman, 1996; Gonzalez and Woods, 1992). The most widely used filter for smoothing noise in radiographs is the median type. This filter, the middle value among the values (elements) of the original operation, will be the output value of the pixel. The median filter offers good performance in noise elimination, without removing relevant discontinuities and without decreasing image sharpness as evidently as mean and gaussian filters (Aoki and Suga, 1997; Aoki and Suga, 1999; Gonzalez and Woods, 1992; Maklashevsky et al., 1998).

Wang and Liao (2002) point out the difficulty in smoothing noise in radiographs due to the variation of gray levels existing in the images, making very difficult the choice of a filter or a smoothing technique that can be used on all radiographic images. However, they state that a median filter with 3×3 and 5×5 operating windows is the most adequate to be applied to radiographs of continuous welds.

Contrast Optimization in Radiographic Images

Radiographic films normally have deficient contrast after exposure during NDT due to various problems like nonuniform radiation caused by the test technique, variation in the thickness of the tested part, inadequate film exposure, and inadequate film processing control, among others (Castleman, 1996).

The digitization process of radiographs can also be responsible for the low contrast of the digital image, mainly in systems that do not have good gray level dynamics. Problems such as focus, reflection and distortion must be controlled effectively. The electronic circuit of the digitizing plate must prevent the decrease of the distribution of gray levels when digitizing the images (Gonzalez and Woods, 1992).

The objective of the contrast improvement stage in radiographs is to enhance the regions in which there are discontinuities without affecting the other regions of the image, thereby guaranteeing that the subsequent segmentation techniques can come out well (Kehoe and Parker, 1990). It should be noted that the radiographic contrast improvement stage comes after noise elimination, so that the noise is not enhanced together with the contrast.

To optimize radiographic contrast, it is common to use a stage normally known as contrast extension (optimization of the distribution of the gray levels of the image through the pixels). To extend the contrast of the radiographic image, Cherfa et al. (1998) used a transformation function applied to the gray tones histogram. The same was done by Merenyi and Heller (1988) to optimize the distribution of gray levels in the radiographs with which they worked. The result of this procedure was satisfactory, improving appreciably the quality of the radiographic images in terms of contrast (Merenyi and Heller, 1988). Recently, Shafeek et al. (2004a; 2004b) reported the use of contrast extension and, sequentially, histogram equalization only in the weld bead indicated in the radiographs to facilitate the subsequent segmentation process. When the extension or histogram equalization of the image is applied only to the region in which the existence of the discontinuity is suspected, then all the nonuniform gray levels existing in the radiograph are eliminated, many times allowing the sequential segmentation only with a simple threshold in this region. However, we stress that the process takes place with human intervention and will operate in a semiautomatic mode.

SEGMENTATION (DISCONTINUITY DETECTION)

Segmentation, which is defined as the process that separates the regions of interest in the image (Castleman, 1996), is normally the last stage in the digital processing of radiographs. The main objective is the elimination of irrelevant information, leaving only the objects of interest in the image, such as, for example, welding discontinuities existing in the weld bead, which in this case is called discontinuity detection. The most common radiographic segmentation techniques generally make use of a series of filters to find significant variations in the pixels of the images that may correspond to the discontinuities. Some of the segmentation techniques are based on edge detection (such as the Canny, Laplacian of Gaussian, Deriche and Prewitt techniques [Castleman, 1996; Gonzalez and Woods, 1992]), as well as techniques known as region growing (Castleman, 1996).

Murakami (1998) describes the use of segmentation techniques for detecting weld discontinuities in radiographs using various types of filters such as smoothing filters, bridge filters, Kirsch, Prewitt, and Sobel operators on contrast filters. He gives an example of a segmented radiograph applying a sequence of these filters. The result was excellent, efficiently detecting the porosity. A great disadvantage of this technique, however, is that the sequence of filters used is different for each type of radiographic image (Murakami, 1998).

Carrasco and Mery (2004) developed a segmentation technique based on noise attenuation filters, morphological mathematical operators, edge detection techniques such as the Canny filter, the Watershed transform, and the distance transform as follows: first, a median filter is used for noise reduction; second, a bottom hat filter is used to separate hypothetical discontinuities from their background; third, the segmented regions are identified by means of binary thresholding; fourth, filters taken from morphological mathematics are used to eliminate oversegmentation; and, fifth, the Watershed transform is used to separate internal regions. The results of the study have generated an area underneath the receiver operating characteristic curve of 0.9358 in a set of 10 images. The best operational point reached corresponds to a detection rate of 87.83% and a false positive rate of 9.40%.

In general, image segmentation plays one of the most important roles in real-world computer vision systems. In the past 40 years, this field has experienced significant growth and progress. Only last year, 194 papers with the words "image" and "segmentation" in the title were indexed by the ISI Web of Science (ISI, 2006). According to our surveys, approaches developed for automated visual testing are tailored to the task; that is, there is no general approach applicable to all cases because the development is an ad hoc process. Segmentation of radiographic images is a very complex task that sometimes does not lead to satisfactory results because there is a fundamental tradeoff between false alarms and missed detections. Most of the techniques used, if not properly controlled, can cause the elimination of important information from the image, leading, for example, to underrating of weld discontinuities and therefore damaging later classification stages structured on the measurement of geometric characteristics. In addition, many published algorithms have been tested with very few images, where the parameters have been tuned manually. Since the reported experiments do not use the same data, it is evident that an objective comparison is very difficult. Additionally, some techniques are not reproducible because the data and code are not available.

FINAL CONSIDERATIONS

Analyzing the main publications in this research area, it can be firmly stated that there are no well established rules which, when followed, will lead to an automatic system of radiographic testing. Several techniques are used by the authors, some of them very similar, as can be seen in the references cited.

In general, almost all the authors use image quality improvement techniques, such as the application of digital filters, before moving on to the detection and classification of the discontinuities. This is quite reasonable, because the better the image quality (with respect to contrast and the absence of noise), the easier will be the stage of segmentation, detection of discontinuities, and later classification of the type of discontinuity found.

In conclusion, on the basis of all the papers described, further development of the segmentation (detection) stage is needed, considering the difficulties that still exist, which will certainly guide future research.

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