State-of-the-Art of Weld Seam Inspection by Radiographic Testing: Part I – Image Processing

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ABSTRACT
Over the last 30 years, there has been a large amount of research attempting to develop an automatic (or semiautomatic) system for the detection and classification of weld defects in continuous welds examined by radiography. There are basically two large types of research areas in this field: image processing, which consists in improving the quality of radiographic images and segmenting regions of interest in the images, and pattern recognition, which aims at detecting and classifying the defects segmented in the images. Because of the complexity of the problem of detecting weld defects, a large number of techniques have been investigated in these areas. This paper represents a state-of-the-art report on weld inspection and is divided into the two parts mentioned above: image processing and pattern recognition. The techniques presented are compared at each basic step of the development of the system for the identification of defects in continuous welds. This paper deals with the first part.

Keywords: Weld defects, nondestructive testing, radiography, automatic weld inspection, image analysis.

1. INTRODUCTION

The first experiments to detect weld defects using X-rays took place at the laboratory scale at Yale University in 1896, barely one year after the dicovery of X- rays by Wilhelm eConrad Röntgen in Germany [1]. However, it was only in 1927 that the first industrial X-ray equipment was developed to carry out these inspection tests on a larger scale. After getting the radiographs, the inspection is done by visual interpretation of the X-ray images, which show radiation energy attenuation as it goes through the object that is being studied. Inspection 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*. Then, during the Second World War, it was used extensively for the inspection of ships, submarines and airplanes. It is estimated that in 1954 in Western Germany about 50% of all welds in *steel constructions* were inspected using X-rays. Even though it is true that in the 1960s there was clarity in relation to quality control programs for welds [2], it was only in 1975 that a weld radiograph was digitized for the first time, and that meant the beginning of automatic visual inspection of welds based on digital image processing techniques.[1] Nowadays, industrial radiography of welds is widely used for the detection of defects in the petroleum, chemical, nuclear, naval, aeronautics and civil construction industries, among others.

The success of weld inspection depends strictly on the quality of the X-ray image, which varies as a function of multiple inspection parameters such as focus-film distance, focus size, film-object distance, use of image intensifying screens, filters, test geometry, exposure time,

[1] It should be mentioned that Shirai published in 1969 an article on algorithms for the inspection of welds, but his proposal made use of photographs (for superficial inspection) and not radiographs to investigate the insoide of the weld.

film type, and chemical film processing, among others [3]. Human visual inspection of weld defects is an extremely difficult task, as reported in the first paper on the subject in 1936 [1]. 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 [4,5]. To minimize this problem numerous investigations on automatic weld inspection appeared making use of the development of computers and digital image processing and pattern recognition techniques, and from image digitization devices such as CCD cameras [6,7], 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 defects examined by X-rays.[2] However, it is pertinent to ask: What is the state of the art of research in this subject? The present paper has as its main purpose to make a brief and objective description of the state-of-the-art in automatic inspection 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 two parts (Part I: image processing, and Part II: pattern recognition), follows the outline shown in Figures 1 and 2, consisting basically of three stages: image acquisition (the fisrt stage); preprocessing, segmentation, feature extraction and detection of defects (the second stage); and classification of the defects found (the third stage) . The first and the second stages will be covered in Part I, while the third will be detailed in Part II. Each stage will be taken up separately, and a table will be made showing the main technical aspects and results obtained by each author. As will be seen in this paper, automatic detection of weld defects is still an unresolved research field, since there is a large variety of situations in which the defects can not yet be recognized by computational algorithms.

[2] Weld inspection using radiographs has become so important, that institutions like the *American Society for Nondestructive Testing* (ASNT) and the *German Society for Nondestructive Testing* (DGZfP) organize congresses devoted solely to this field of research.

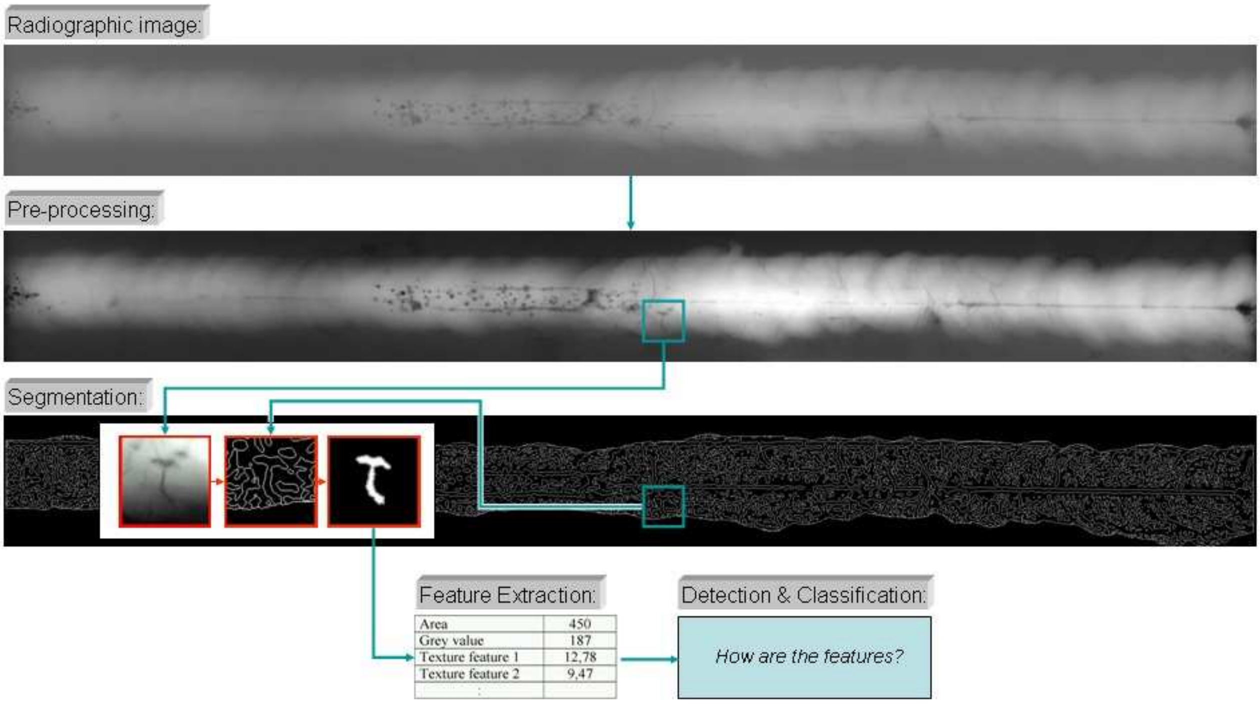

FIGURE 1: *Schematic diagram of the detection of defects in welds.*

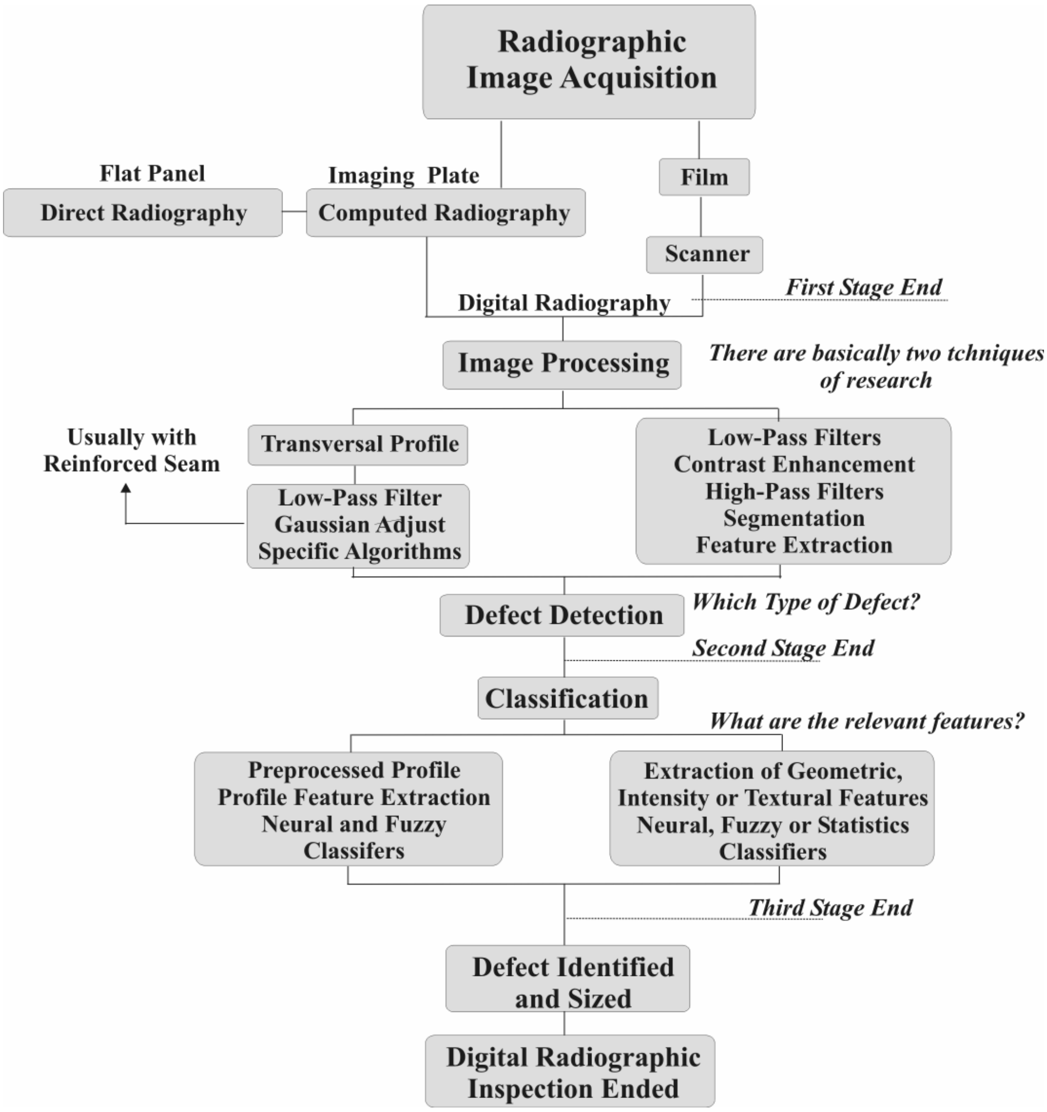

FIGURE 2: *Stages of Automatic Inspection of Weld Seam by Digital Radiography*.

2. 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 [6, 7, 8]. There are some methods for digitizing of radiographs that will be described briefly below.

2.1 Photography with CCD (Charge-Coupled Device) 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 [9, 10, 11, 12]. In this process, the energy of the light 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 (resolution of gray levels). 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. [9] describe the process of obtaining high contrast images during digitization using a CCD camera. These processes of digitization of radiographs have already become outdated and are practically not used, because the spatial and gray levels resolutions are normally inferior when compared with those obtained by other more modern methods (such as those described in the following sections). However, Shafeek [13,14] has used the method of Suga et al. with good results in his recently published work.

2.2 Digitization of X-Ray Films through their Appropriate Scanners

Currently there are several types of appropriate scanners for digitizing radiographs that operate on the light transmission mode. In this case, the films are placed in the digitizing area, which can be of the *flat-bed* 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 device in the bottom part of the scanner. The resolution and density limits of the apparatus,[3] as well as the capture driver, define the characteristics of the digitized radiographic image. There are also scanners that use laser beams as light sources, allowing a much greater concentration of light photons, and therefore greater precision for digitizing high density films.

Cherfa et al. [15], Li & Liao [16] and Silva [17] used scanners in their work to digitize radiographs. Liao & Li [16] and Wang & Liao [18] used a scanner that allowed a spatial resolution of 70μm pixels, each pixel having 12 bits (4096 levels of gray).

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

2.3 Digitization of Phosphor Plates

In addition to film digitization, there is the digitization of plates containing crystals of photo-stimulated phosphor in which, when exposed to X-rays or gamma rays, some of the electrons go to a higher semi stable 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 inspection process as well as to greater speed in the process of image visualization [19].

3. IMAGE PROCESSING

The quality of radiographic images is an important factor in the detection of weld defects, and it is normally evaluated through the use of image quality indicators (IQIs) [7]. Factors such as film type, film density, focus-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 defects [7].

[3] There are now scanners capable of digitizing films with optical density up to 4.0.

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 defect 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 inspection [2].

After digitizing the images, there is the possibility of processing them with the application of digital image filters, eliminating or smoothing the existence of 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, for example, the underrating of a defect or even its exclusion from the image.

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

3.1 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 [2] or in the digitization process, the latter known as electronic noise. In this stage low-pass filters are normaly applied, since noise is characterized by high frequencies [7,8]. 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 has good performance in noise elimination, without removing relevant defects and without decreasing image sharpness as evidently as mean and Gaussian filters [8, 10, 11, 20].

Wang [18] points out the difficulty that there is 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, he states that the median filter with 3x3 and 5x5 operating windows is the most adequate to be applied to radiographs of continuous welds [18].

3.2 Contrast Optimization in Radiographic Images

Radiogrphic films normally have deficient contrast after the test due to various problems like nonuniform radiation caused by the inspection technique, variation in the thickness of the inspected part, inadequate film exposure, and inadequate film processing control, among others [7].

The digitization process of radiographs can also be responsible for the low contrast of the digital image, mainly systems that do not have good gray level dynamics. Problems such as out-of-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 [8].

The objective of the contrast improvement stage in radiographs is to enhance the regions in which there are defects, without affecting the other regions of the image, thereby guaranteeing that the subsequent segmentation techniques can come out well. [21]. 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. [15] used a transformation function applied to the gray tones histogram. The same was done by Merenyi & Séller [22] 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 [22]. Recently, Shafeek [13,14] 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 and/or histogram equalization of the image is applied only to the region in which the existence of the defect is suspected, then all the nonuniform gray-level existing in the radiograph is 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.

3.3 Segmentation (Detection of Defects)

Segmentation, which is defined as the process that separates the regions of interest in the image [7], 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 defects existing in the weld bead, which in this case is called defect 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 defects. Some of the segmentation techniques are based on edge detection (example: *Canny*, Laplacian of Gaussian, *Deriche*, *Prewwitt* [7,8]), as well as techniques known as region growing [7].

Murakami [12] describes the use of segmentation techniques for detecting weld defects in radiographs using various types of filters such as smoothing filters, bridge filters, Kirsch, Prewitt, Sobel operators on contrast filters. He gives an example of segmented radiograph applying a sequence of these filters. The result was excellent, efficiently detecting the porosity defect. A great disadvantage of this method, however, is that the sequence of filters used is different for each type of radiographic image [12].

Carrasco & Mery [23] developed a segmentation method 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 flaws from their background; third, the segmented regions are identified by means of binary thresholding; fourth, filters taken from morphological mathematics are used to eliminate over-segmentation; and fifth the Watershed transform is used to separate internal regions. The results of the study have generated an area underneath the ROC (Receiver Operating Characteristic) curve of 0.9358 in a set of ten 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 last 40 years, this field has experienced significant growth and progress.

Only last year, 194 papers with the word "image" and "segmentation" in the title field were indexed by the Web of Science of ISI. According to our surveys, approaches developed for automated visual inspection are tailored to the inspection task, i.e., 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 which sometimes does not lead to satisfactory results because there is a fundamental trade off between false alarms and miss 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 defects and therefore damaging later classification stages structured on the measurement of geometric characteristics. In addition, many published algorithms have been tested in a 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 methods are not reproducible because the data and code are not available.

4. 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 inspection. 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 [9, 10, 11, 12, 18, 20, 22, 24] use basically image quality improvement techniques such as the application of digital filters before moving on to the detection and classification of the defects. 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 defects, and later classification of the type of defect 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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