NDT&E International 72 (2015) 1–9

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Automatic weld defect detection method based on Kalman filtering for real-time radiographic inspection of spiral pipe

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A R T I C L E I N F O

Article history:
Received 3 November 2014
Received in revised form
7 January 2015
Accepted 11 January 2015
Available online 21 January 2015

Keywords:
Non-destructive testing
Radiographic image sequence
Weld defect
Automatic detection
Kalman filtering

A B S T R A C T

A method based on Kalman filtering is proposed for weld defect detection in real-time radiographic NDT of spiral pipes. The existence of the image noises and the inhomogeneity of the background contrast induce numerous false alarms. In this paper, the trajectory continuity of the defects in the image sequence is detected by Kalman filtering for the identification of true defects. Potential defect regions without continuous motion are considered as false alarms and are eliminated. Experiments are performed to demonstrate the adaptability of the proposed method. The robustness of the method is also verified under unstable detection velocity.

1. Introduction

Radiographic inspection is one of the important Non-Destructive Testing (NDT) methods for weld defect detection. The conventional radiographic weld testing with film is uneconomic, time-consuming, and non-eco-friendly. Digital radiographic methods that allow real-time inspection and digital storage have been developed. The human interpretation is being widely applied for the detection of weld defects. Experienced operators are required to evaluate the dynamic radiographic images acquired and displayed. The human interpretation of radiographic images runs the risk of being highly subjective. The performance of inspection is expertise-dependent, inconsistent, and can easily be affected by fatigue. Therefore, efforts have been devoted to the research of automatic radiographic inspection via image analysis. It can possibly achieve consistent performance of defect detection in real-time, with better objectivity and efficiency. The disadvantages are, however, the inflexibility and the lack of robustness to any change of the inspection situation.

The methods of defect detection include local threshold method, morphologic feature extraction method, region growing, different kinds of filtering, etc. For the image acquired by film scanning or static inspection with sufficient X-ray exposure time, details are contained in the digitized images, therefore the recognition of the defect characteristics is possible, via the image analysis methodologies. Gray-level features [1], geometric features [2], textural features [3] are investigated and extracted [4]. Pattern recognition methods are employed for the identification of weld defects after the extraction of features [5]. It should be pointed out that the dynamic X-ray inspection performed in real-time usually lacks of sufficient image quality, compared with the image acquisition methods such as film scanning or static X-ray imaging. The information level in aspects of both gray-level resolution and spatial resolution is limited. It raises difficulties to the automatic detection of the weld defects [6]. When applied to real-time radiographic detection of weld defects, the segmentation and detection techniques would encounter the following problem. Because of uneven background, image noise, and low contrast, the image processing method may target the regions of true defects along with false alarms. The attempt to extract true defects which have low contrast has to contend with the appearance of false positives caused by the existence of noise or background regions with a similar gray level. The trade-off between false alarms and miss detections is one of the major problems from which the automated X-ray testing suffers [7]. Improving the detection rate while keeping the false positives under a low level has always been the focus of research efforts.

The extracted potential defect regions, possibly include both true defects and false positives, have similar contrast and geometric characteristics. The information from a single frame is no longer sufficient for distinguishing true defects from false alarms. Several studies have recently investigated different methods for the elimination of false alarm by utilizing complementary information about the true defects. Mery et al. [8] studied the tracking

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http://dx.doi.org/10.1016/j.ndteint.2015.01.002
0963-8695/

of defects in different views to reduce the false positive rate. Their recent publication [9] proposed a multiple view method without system calibration for the defect detection of a complex object. The potential regions are extracted from different views by X-ray inspection. Similarity and geometrical multiple-view constraints are used for matching and tracking these regions for filtering out the false alarms. The method uses spacial geometry as complementary information for the distinguish of true defects and false alarms. In the continuous detecting of pipe welds, temporal continuity can be used as complementary information. Sun et al. [10] developed a method based on fuzzy pattern recognition for defect detection. The spatial characteristics on defect neighborhood such as variance and contrast are used to solve the dilemma between locating all the true defects and avoiding false alarms. Shao et al. [11] proposed a line-detecting method for tracking the true defects in a sequence of radiographic images. Hough transform is applied for detecting the linear trajectory of the true defects in the image sequence. The method shows good performance in the on-line detection of spiral pipes under the condition of a constant velocity. But as the method depends on the linearity of defect trajectory, the variation of detection velocity can cause miss detection. The method risks the decrease of detection rate in practical application. A method with better robustness needs to be developed.

In this paper, a method based on Kalman filtering is proposed. The idea is to detect the continuity of the defect motion in the image sequence. Only the defects with continuous trajectory (need not to be linear) in the sequence can be identified as true defects. Section 2 describes the extraction of potential defect regions, which are segmented by gray-level thresholding and considered as candidates for the following detection. Section 3 presents the Kalman filtering method for distinguishing true defects from false alarms and also details the developed algorithm. Section 4 shows the experimental results which demonstrate the performance of the proposed method, discusses its adaptability and robustness. Finally in Section 5, the conclusion gives a brief summary of the paper.

2. Extraction of potential defect regions

The potential defect regions are extracted by filtering and thresholding after the segmentation of weld seam area. It can be considered as a preparative step for the distinguish of true defects and false alarms.

2.1. Seam segmentation

The first step of extracting potential defect regions is the segmentation of weld seam area. The processing that follows can only take place within the weld seam. The weld seam area has a relatively lower average of gray level than the rest of the image. A simple thresholding followed by morphology operations is applied to segment the weld seam region. By using the Prewitt operator for edge detection, the weld edges are extracted. The upper edge and the lower edge of the weld area determine the segmentation of the seam.

2.2. Potential defect segmentation

The operator is designed for the detection of potential defects. Eq. (1) shows the configuration of the designed operator, where σ represents the scale of the operator, a represents the size of the region that the operator covers. σ can be set to any value in [3,5]. A two dimensional convolution is applied between the radiographic image and the operator L_σ.

$$L_\sigma(x,y) = -\frac{(x-a/2)^2+(y-a/2)^2-2\sigma^2}{\sigma^4} e^{-(x-a/2)^2+(y-a/2)^2/2\sigma^2} \quad (1)$$

The result of the convolution shows the response of the image to the operator, where the potential defect region has been smoothed and emphasized. The thresholding of the convolution result segments the image into potential defect regions and backgrounds.

3. Kalman filtering for defect motion tracking

The extracted potential defect regions have similar gray-level distribution and geometric characteristics. True defects are difficult to be distinguished from the false alarms. It is necessary to take account of the defect motion continuity for the elimination of the false alarms. The method is proposed and detailed in this section.

The Kalman filtering method is proposed for tracking the motion of true defects. The idea is to detect the trajectory continuity of defects in the image sequence. The state space is firstly formed for the establishment of the system model. Then the Kalman filtering is applied to track the motion of the defects. After initializing the state vector and the transform matrices, we track the displacement of the defects frame by frame, in steps of prediction, observation and update. A detailed algorithm is also developed for the application of the method.

3.1. State-space formulation

The extracted potential defect regions are considered as the objects to be tracked. The system is formulated using the concept of state space. The state vector of an object is denoted by x_k^i; the subscript $k=1,2,\ldots,K$ denotes the index of radiographic image frame, the subscript $i=1,2,3$ denotes the index of blob extracted in the frame. The state vector x_k^i is defined as the minimal set of data which is sufficient to uniquely describe the current state and the current dynamical behavior of the object. To describe the potential defect blob, the following data is needed: the current position of the weight center of the blob in the image coordinates, the current velocity of the blob, and the shape descriptor of the blob (i.e. the minimum circumscribed ellipse parameters). The process equation is defined as in Eq. (2), where $F_{k+1,k}$ is the state transition matrix between the kth frame and the $(k+1)$th frame, ω_k is the noise added in the process. The measurement equation is defined as in Eq. (3), where H_k is the measurement matrix, y_k is the observation vector in the kth frame, and υ_k is the measurement noise.

$$x_{k+1}^i = F_{k+1,k} x_k^i + \omega_k \quad (2)$$

$$y_k^i = H_k x_k^i + \upsilon_k \quad (3)$$

3.2. Kalman filtering

Kalman filtering is an approach using the current state of the system for the prediction of its future behavior. It is an effective technique for object tracking in machine vision [12,13]. The potential defect regions can be true defects or false alarms induced by noises or uneven backgrounds. In the image sequence, the appearance of true defects will form a continuous trajectory, while false alarms turn out to appear randomly in irregular positions. The Kalman filtering approach can help track the true defects. The state vector and its covariance matrix are predicted using the current state (of the kth frame) and the transition matrix. The