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A non-reference evaluation method for edge detection of wear particles in ferrograph images

Jingqiu Wang, Ju Bi, Lianjun Wang, Xiaolei Wang *

Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

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A B S T R A C T

Edges are one of the most important features of wear particles in a ferrograph image and are widely used to extract parameters, recognize types of wear particles, and assist in the identification of the wear mode and severity. Edge detection is a critical step in ferrograph image processing and analysis. Till date, there has been no single algorithm that guarantees the production of good quality edges in ferrograph images for a variety of applications. Therefore, it is desirable to have a reliable evaluation method for measuring the performance of various edge detection algorithms and for aiding in the selection of the optimal parameter and algorithm for ferrographic applications. In this paper, a new non-reference method for the objective evaluation of wear particle edge detection is proposed. In this method, a comprehensive index of edge evaluation is composed of three components, i.e., the reconstruction based similarity sub-index between the original image and the reconstructed image, the confidence degree sub-index used to show the true or false degree of the edge pixels, and the edge form sub-index that is used to determine the direction consistency and width uniformity of the edges. Two experiments are performed to illustrate the validity of the proposed method. First, this method is used to select the best parameters for an edge detection algorithm, and it is then used to compare the results obtained using various edge detection algorithms and determine the best algorithm. Experimental results of various real ferrograph images verify the effectiveness of the proposed method.

1. Introduction

With the development of modern mechanical equipment in the direction of large scale, high productivity, and high reliability, predictive maintenance procedures based on the machine conditions are necessary for decreasing the occurrence of over-maintenance as well as to prevent the sudden breakdown of machines. Ferrography has been proven to be an effective means of wear-condition monitoring and fault diagnosis of machines such as aero-engines and mining equipment. This technique is used to determine the wear condition and wear mechanisms of machines through qualitative and quantitative analysis on the amount, size, shape, colour, and texture of the wear particles (wear debris) contained in the lubricating or hydraulic system [1,2]. However, the dependency on human expertise for the analysis and interpretation limits the application and potential of this method in the industry [3]. The development of computer image analysis could provide a solution for the aforementioned problems and greatly improve the accuracy and efficiency of ferrograph analysis [4,5].

* Corresponding author.
E-mail address: wxl@nuaa.edu.cn (X. Wang).

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In the last three decades, many efforts have been focused on the application of image processing techniques for the feature extraction and classification of wear particles [6–11]. Analysis systems based on human–computer interaction, such as the CAVE [12], CASPA [13], and SYCLOPS [14], as well as expert systems based on 3D particle analysis [15] have been developed.

CAVE is an interactive control system that is mostly used to carry out analysis on single particles. It applies Fourier transforms and the curvature analysis of the outline of a particle as the input parameters into a neural network, which then classifies the particle's shape.

CASPA was developed as an off-line debris classifier. The user is prompted to answer a series of text-based questions concerning the morphology of the particle. Then, it classifies the wear particles in terms of the wear mode by using an expert system.

SYCLOPS is a semi-automated wear-debris classification system. It classifies the characteristics of the particles by matching them to a selection of stylized images. For example, by defining the particle's shape as regular, irregular, or elongated, the user can determine which corresponding image resembles the shape of the particle.

Peng et al. developed an expert system based on 3D particle analysis for interpreting the analysis data of wear debris to assist machine-condition monitoring and fault diagnosis. However, it is difficult to obtain 3D image analysis data in most application fields.

Recently, efforts have been made to develop an automatic and reliable wear particle analysis system [16,17]. The application of such systems should significantly reduce the inspection time and the requirement of the inspector's expertise [18]. In such an automatic system, wear particles are first segmented from each other, then the features and parameters are extracted, and finally, the wear particles are classified and recognized based on the extracted features.

Edges are one of the most important features of wear particles in a ferrograph image, and they provide a concise and accurate representation of the wear particle boundaries. From the edges, more complicated features and parameters of the wear particles can be extracted. For example, the parameters of area, perimeter, and aspect ratio help in classifying the type of wear particles and subsequently, the wear mode and severity.

Edge detection is a fundamental operation performed in lower-level image processing and computer vision systems. Popular edge detection algorithms or detectors include the Sobel, Robert, Prewitt, Laplacian, LoG, and Canny [19]; currently, the wavelet [20], grey relational operator [21], and marker-watershed algorithms [22] are also applied for the edge detection of wear particles.

Although the performance of the majority of edge detectors is acceptable for simple and noise-free images, the case is different for ferrograph images. For various practical environments, the size, colour, and noise of ferrograph images are very different, which significantly increases the complexity involved in edge detection. It is known that the appearance of the edges of wear particles in an image varies greatly. The edges vary with respect to the types of wear particles and their shapes in the images. The edges may be crowded, blurred, or sparse. After the edge detection, the edge image may still contain some isolated edge points or broken segments. Fig. 1(a) shows an original ferrograph image containing wear particles of various sizes, outlines, brightness, and surface textures. Fig. 1(b)–(d) show the results of the edge detection performed using the Sobel, LoG, and Canny detector, respectively. When the Sobel detector is used, as shown in Fig. 1(b), it generates several false edges for the particles with textures on their surfaces, and the edges of the wear particles are not single-pixel-wide. When using the LoG detector, some edges tend to be lost owing to blurring, and it also generates several false edges, as shown in Fig. 1(c). When using the Canny detector, the edges are detected single-pixel-wide; however, the blurred edges are lost, which results in a discontinuous and unclosed outline of wear particles, as shown in Fig. 1(d).

Till date, there has been no single detection algorithm that guarantees the production of good quality edges in ferrograph images for a variety of applications. Therefore, it is desirable to have a reliable evaluation method for measuring the performance of various edge detection algorithms and for aiding the selection of the optimal parameter and algorithm for ferrographic applications.

The types of edge evaluation methods can be divided into subjective and objective evaluations. Subjective evaluation usually involves the evaluation of edge detectors by observers; however, it is inevitably expensive with respect to time and

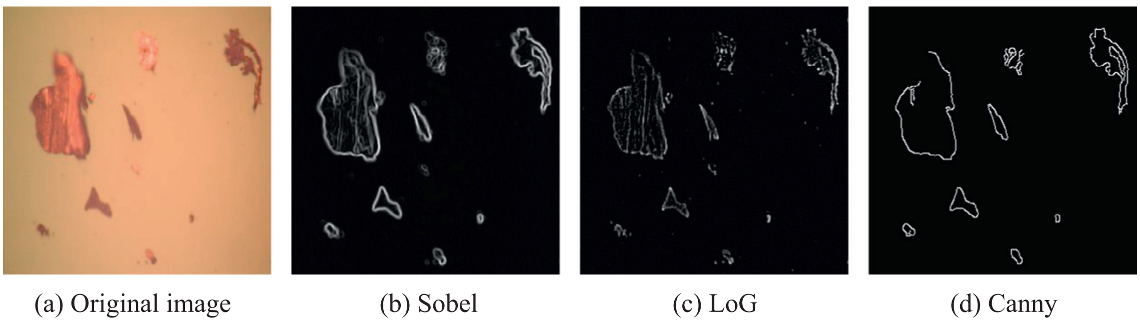

Fig. 1. Typical ferrograph image and results of edge detection.