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Adaptive vision-based crack detection using 3D scene reconstruction for condition assessment of structures

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ABSTRACT

Current inspection standards require an inspector to travel to a target structure site and visually assess the structure's condition. This approach is labor-intensive, yet highly qualitative. A less time-consuming and inexpensive alternative to current monitoring methods is to use a robotic system that could inspect structures more frequently, and perform autonomous damage detection. In this paper, a vision-based crack detection methodology is introduced. The proposed approach processes 2D digital images (image processing) by considering the geometry of the scene (computer vision). The crack segmentation parameters are adjusted automatically based on depth parameters. The depth perception is obtained using 3D scene reconstruction. This system extracts the whole crack from its background, where the regular edge-based approaches just segment the crack edges. This characteristic is appropriate for the development of a crack thickness quantification system. Experimental tests have been carried out to evaluate the performance of the proposed system.

1. Introduction

1.1. Motivation

Civil infrastructure system assets represent a significant fraction of the global assets and in the United States are estimated to be worth $20 *trillion*. These systems are subject to deterioration due to excessive usage, overloading, and aging materials, as well as insufficient maintenance and inspection deficiencies. Bridges constitute one of the major civil infrastructure systems in the U.S. According to the National Bridge Inventory (NBI), more than 10,400 bridges are categorized as structurally deficient [1]. There is an urgent need to develop effective approaches for the inspection and evaluation of these bridges. In addition, periodical inspections and maintenance of bridges will prolong their service life [2].

Visual inspection is the predominant method used for the inspection of almost all infrastructure systems. It is a subjective process that relies on an inspector's experience and mental focus, making it highly prone to human error. The development of automated inspection technology can overcome these shortcomings.

In this study, a novel image-based crack detection approach is introduced that includes autoadaptive features that have not been used in previous crack detection systems. This approach can be used as initial step towards an autonomous crack quantification approach. The field implementation which is the main focus of this study, makes the current study different from other proposed crack detection techniques where the camera-object distance and the image contrast can be controlled. Unlike previous studies (e.g., finding cracks in paintings), the specimen under inspection cannot be investigated in a laboratory environment, and the 3D depth perception of the scene is used to adaptively detect cracks.

1.2. Background

An automatic crack detection procedure in welds based on magnetic particle testing [3] was introduced by Ho et al. in 1990 [4]. This method can only be used on ferromagnetic materials. First, the testing surface is sprayed with white paint to reduce the initial noise of subsequently captured images. Next, a magnetic field is applied to the weld. Then magnetic ink made of small magnetic particles suspended in oil is sprayed over the testing surface. The change of flux density at the crack causes the magnetic particles to trace out the shape of the crack on the weld surface. Lastly, an image of the prepared surface is captured and cracks are detected by means of the Sobel edge detection operator [5,6] and by implementing a boundary tracing algorithm. The results were satisfactory as reported by Ho et al. [4], but clearly this technique has drawbacks since a preprocessing step is required.

Tsao et al. [7] composed image analysis and expert system modulus to detect spalling and transverse cracks in pavements.

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Kaseko et al. [8] and Wang et al. [9] used the image processing and neural network techniques to detect defects in pavements.

Siegel and Gunatilake [10] developed a remote visual inspection system of aircraft surfaces. To detect cracks, their proposed algorithm detects rivets, since cracks propagate on rivet edges. Multi-scale edge detection is used to detect the edges of small defects at small scales and the edges of large defects at large scales. By tracing edges from high scale to low scale, it is possible to define the propagation depth of edges. Using other features based on wavelet transformation [11,12] and a trained back-propagation neural network [13] cracks can be classified from other defects such as scratches. Corroded regions can also be detected by defining features based on 2D discrete wavelet transformation of the captured images and using a neural network classifier [10].

Nieniewski et al. [14] developed a visual system that could detect cracks in ferrites. A morphological detector based on top-hat transform [15] detects irregular changes of brightness, which could lead to crack detection. *k*-Nearest Neighbors [13] is used as a classifier to classify cracks from grooves. The outcome of this study is very promising, and this technique is quite robust despite the presence of noise, unlike other edge detection operators used for crack extraction.

Moselhi and Shehab-Eldeen [16] used the image analysis techniques and the neural network to automatically detect and classify the defects in sewer pipes. Chae [17] proposed a system consisting of image processing techniques along with the neural networks and fuzzy logic systems for automatic defect (including cracks) detection of sewer pipelines.

Benning et al. [18] used photogrammetry to measure the deformations of reinforced concrete structures. A grid of circular targets is established on the testing surface. Up to three cameras capture images of the surface simultaneously. The relative distances between the centers of adjacent targets make it possible to monitor the evolution of cracks.

Abdel-Qader et al. [19] analyzed the efficacy of different edge detection techniques in identifying cracks in concrete pavements of bridges. They concluded that the Fast Harr Transform (FHT), which is a wavelet transform with mother wavelet of Harr, has the most accurate crack detection capability in contrast with Fast Fourier transform, Sobel, and Canny edge detection operators [20,21].

A study on using computer vision techniques for automatic structural assessment of underground pipes has been done by Sinha et al. in 2003 [22]. The algorithm proposed by Sinha et al. [22] consists of image processing, segmentation, feature extraction, pattern recognition, and a proposed neuro-fuzzy network for classification.

Giakoumis et al. [23] detected the cracks in digitized paintings by thresholding the output of the morphological top-hat transform. Sinha and Fieguth [24] detected the defects in underground pipe images by thresholding the morphological opening of the pipe images using different structuring elements. Abdel-Qader et al. [25] proposed algorithms based on Principal Component Analysis (PCA) to extract cracks in concrete bridge decks.

Yu et al. [26] introduced an image-based semi-autonomous approach to detect cracks in concrete tunnels. Yamaguchi and Hashimoto [27] proposed a crack detection approach based on a percolation model and edge information. Chen et al. [28] introduced a semi-automatic measuring system for concrete cracks using multi-temporal images.

Fujita and Hamamoto [29] proposed a crack detection method in noisy concrete surfaces using probabilistic relaxation and a locally adaptive thresholding. Jahanshahi et al. [30] surveyed and evaluated several crack detection techniques in conjunction with realistic infrastructure components.

Guo et al. [31,32] developed an automatic defect detection approach based on interpreting the images or videos that were captured for sewer pipeline inspection and condition assessment. Brilakis et al. [33] outlined a framework for automatic recognition of exposed reinforcement, concrete columns, air pockets, and potholes based on their visual attributes. Zhu et al. [34] developed a system to retrieve the concrete crack properties, such as length, orientation and width, for automated post-earthquake structural condition assessment.

1.3. Contribution

In all of the above studies, many important parameters (e.g., camera-object distance) are not considered or assumed to be constant. In practical circumstances, the image acquisition system often cannot maintain a constant focal length, resolution, or distance to the object under inspection. In the case of nuclear power plants, for instance, the image acquisition system needs to be located a significant distance from the reactor site. To detect cracks of a specific thickness, many of the parameters in these algorithms need to be adaptive to the 3D structure of a scene and the attributes of the image acquisition system; however, no such study has been reported in the open literature. The proposed approach in this study gives a robotic inspection system the ability to detect cracks in images captured from any distance to the object, with any focal length or resolution. The proposed crack detection system extracts the whole crack as opposed to edge-based approaches where just the edges are segmented. This characteristic makes the current study appropriate for crack thickness quantification which is under development by the authors.

In human vision, depth perception allows a person to estimate the size of an object based on the distance to the object. In this study, a contact-less crack detection approach based on depth perception is introduced to segment crack-like patterns. First, several pictures of a scene are captured from different views. By solving the Structure from Motion (SfM) problem [35], the sparse structure of a scene as well as the camera's position, orientation, and internal parameters for each view are determined. By scaling the reconstructed sparse 3D model of a scene, the depth perception is obtained. Subsequently, a morphological crack segmentation operator is introduced. The structuring element parameter for this operator is automatically adjusted based on the camera focal length, object-camera distance, camera resolution, camera sensor size, and the desired crack thickness. Appropriate features are extracted and selected for each segmented pattern using the Linear Discriminant Analysis (LDA) [36] approach. A trained Neural Network (NN), a Support Vector Machine (SVM), and a nearest-neighbor classifier are used to classify real cracks. The performance of these classifiers in the problem of interest is discussed. Finally, a multi-scale approach is introduced to obtain a crack map. The proposed methodology is also effective for other pattern analysis purposes (e.g., texture analysis) which are not discussed in this paper.

1.4. Scope

Section 2 discusses the proposed adaptive crack detection. The components of the proposed system, including interaction of different image acquisition parameters, the 3D scene reconstruction, segmentation, feature extraction and pattern classification are discussed in Sections 2.1, 2.2, 2.3, 2.4 and 2.5, respectively. The construction of the multi-scale crackmap is explained in Section 3. Experimental results and discussion are presented in Section 4. Section 5 includes the summary of the paper.

2. Adaptive crack detection

An adaptive crack detection procedure is proposed in this study. This system is adaptive because based on the image acquisition specifications, camera-object distance, focal length and image resolution, it automatically adjusts its parameters to detect cracks of