ARTICLE IN PRESS

Alexandria Engineering Journal (2017) **xxx**, xxx–xxx

HOSTED BY

ELSEVIER

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Crack detection using image processing: A critical review and analysis

Arun Mohan [a,*], **Sumathi Poobal** [b]

[a] *Gurudeva Institute of Science and Technology (GISAT), Kottayam, Kerala*
[b] *KCG College of Technology, Chennai, India*

Received 29 November 2016; revised 30 December 2016; accepted 14 January 2017

KEYWORDS

Crack detection;
Image processing;
Median filter;
Segmentation;
Feature extraction

Abstract Cracks on the concrete surface are one of the earliest indications of degradation of the structure which is critical for the maintenance as well the continuous exposure will lead to the severe damage to the environment. Manual inspection is the acclaimed method for the crack inspection. In the manual inspection, the sketch of the crack is prepared manually, and the conditions of the irregularities are noted. Since the manual approach completely depends on the specialist's knowledge and experience, it lacks objectivity in the quantitative analysis. So, automatic image-based crack detection is proposed as a replacement. Literature presents different techniques to automatically identify the crack and its depth using image processing techniques. In this research, a detailed survey is conducted to identify the research challenges and the achievements till in this field. Accordingly, 50 research papers are taken related to crack detection, and those research papers are reviewed. Based on the review, analysis is provided based on the image processing techniques, objectives, accuracy level, error level, and the image data sets. Finally, we present the various research issues which can be useful for the researchers to accomplish further research on the crack detection.

1. Introduction

Engineering structures like concrete surface, beams are often subjected to fatigue stress, cyclic loading, that leads to the cracks that usually initiate at the microscopic level on the structure's surface. The cracks on the structure reduce local stiffness and cause material discontinuities [51,52]. Early detection allows preventive measures to be taken to prevent damage and possible failure [11]. Crack detection is the process of detecting the crack in the structures using any of the processing techniques. The crack detection can be made in two ways. They are Destructive Testing and Non-Destructive testing. By incorporating the visual examination and surveying tools, surface condition deficiencies are evaluated [11].

The objective of the type, number, width and length of the cracks on the structural surface shows the earliest degradation level and carrying capacity of the concrete structures [17].

For fast and reliable surface defect analysis, Automatic crack detection is developed instead of the slower subjective traditional human inspection procedures. Thereby a safer survey methodology is adapted [32]. Automatic crack detection is

* Corresponding author.
E-mail address: arunmohan.0127@gmail.com (A. Mohan).

Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2017.01.020
1110-0168 © 2017 Faculty of Engineering, Alexandria University. Production and hosting by Elsevier B.V.

very effective for Non-destructive testing. By manual inspection, it is difficult to assess deterioration objectively [48]. The automated crack detection can be done using some of the Non-destructive testing techniques like (i) Infrared and thermal testing, (ii) Ultrasonic testing, (iii) Laser testing, and (iv) Radiographic testing [48].

There is an increasing interest in image-based crack detection for non-destructive inspection. Some of the difficulties in the image based detection are because of the random shape and irregular size of cracks and various noises such as irregularly illuminated conditions, shading, blemishes and concrete spall in the acquired images. Because of its simplicity in the processing, many of the image processing detection methods were proposed. These methods are classified into four categories, namely integrated algorithm, morphological approach, percolation-based method, and practical technique [40].

In this research, a detailed survey is conducted to identify the research challenges and the achievements till in the field of crack detection. Accordingly, 50 research papers are taken related to crack detection, and those research papers are reviewed. The organization of this survey initially starts up with the general architecture of image processing based crack detection, and then survey of the various papers based upon the image type used. Followed by the analysis based on objective, dataset, error and accuracy level are listed below.

2. Crack detection using image processing: Architecture

This section provides the basic architecture for the crack detection using the image processing technique [40]. The major advantage of the image based analysis of the crack detection is that by using the image processing technique it provides accurate result compared to the conventional manual methods [9]. The processing difficulty of the crack detection completely depends on the size of the image. Recent digital cameras have the image resolution beyond 10 megapixels. This increase in resolution enables the acquisition of detailed images of concrete surfaces. By using the trendy cameras of commercial purpose, a wide range of a concrete surface can be acquired in a single shot. For inexpensive applications, a wide range image can be used for the practical crack detection [2].

Fig. 1 shows general architecture for crack detection based on the image processing. The steps in the image processing technique are as follows: (1) initially collect the image of the structure which will be subjected to the crack detection process using the camera or any sources. (2) After the image acquisition, the collected images are pre-processed within which the methodologies like segmentation are done there by making it an efficient one for the image processing procedure. (3) In the image processing, some of the techniques are employed to process the deducted image sample. (4) The crack detection will be noticed here on the structure using the result of the processed image. (5) Crack feature extraction is the step in which the detected cracks are separated based on the width, depth and the direction of propagation of the crack.

3. Survey

This section provides the review of the image based crack detection techniques based on the type of the image used. Some of the image types investigated here are Camera image, IR image, Ultrasonic Image, Time of Flight Diffraction image, Laser image and various other distinctive image types.

3.1. Camera based image processing techniques

This section briefs about processing techniques based on the camera image for the detection of the cracks in the engineering structures. Many papers are reviewed here under the camera image as the input.

Yiyang et al. [4] have proposed a crack detection algorithm based on digital image processing technology. By pre-processing, image segmentation and feature extraction [4], they have obtained the information about the crack image. In [4], Threshold method of segmentation was used after the smoothening of the accepted input image. To judge their image, they have calculated the area and perimeter of the roundness index. Then by the comparison, they have evaluated the presence of the crack in the image.

Even though many of the commercial camera based image processing techniques dictate only upon the pre-processing, some techniques concentrate on the integration algorithm were the feature extraction would be made. Adhikari et al. [5] developed a model that numerically represents the defects. Their integration model consists of crack quantification & detection, neural network, and 3-D visualization model respectively. An image stitching algorithm developed by Brown and Lowe [53] has been adopted which works on feature based registration. They have used skeletonization algorithm for the retrieval of the crack segments. The detection of the crack based upon the width and the length was completely based on the crack quantification model evaluation. Also, the integrated model as proposed by them has, crack length and change detection supported by neural networks to predict crack depth and 3Dvisualization of crack patterns.

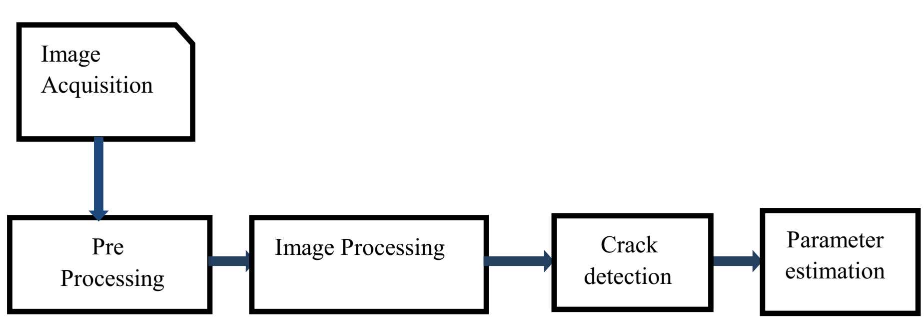

Fig. 1 The architecture of image processing based crack detection.

Alam et al. [6] have proposed a detection technique by the combination of the digital image correlation and acoustic emission. The former method gives a very precise measurement of surface displacements, thus crack openings and crack spacing were determined. In order to complement that method and to investigate damage mechanisms, acoustic emissions resulting from internal damage were also analyzed. A manual grouping method (similar to K-means method) was used to identify different classes of AE energy released from the Beams of three different sizes. In their methodology, they have used three different beam proportionalities for the effectiveness of the output.

Iyer et al. [7] have designed a three-step method for the crack detection from the high contrast images. The proposed method detects the crack like pattern in the noisy environment using curvature evaluation and mathematical morphology technique. It was based on mathematical morphology and curvature evaluation that detects crack-like patterns in a noisy environment. In their study, segmentation is done defining the crack like pattern with respect to a precise geometric model. Linear filtering was performed after cross curvature evaluation to distinguish them from analogous background pattern. They have identified the irregularity sequentially by the Geometry-based recognition crack features.

The Filtering techniques adopted in the image processing scheme also alter the overall efficiency of the process. Salman et al. [12] proposed an approach to automatically distinguish cracks in digital images based on the Gabor filtering. Multi-directional crack detection can be achieved by high potential Gabor filter. The Gabor filter is a highly potential technique for multidirectional crack detection. The image analysis of the Gabor filter function was directly related to the manual visual perception. Once filtering was completed, the cracks aligned to different directions are detected. They have a detection precision of 95% for their proposed methodology. Shan et al. [17] have presented stereovision-based crack width detection. In their approach, two cameras were used unlike other proposals reviewed here. They have recovered coordinates of the crack edge by using those stereo vision cameras. They have used Canny-Zernike algorithm to obtain the image coordinates of a crack edge on the recovered coordinate of the stereo vision cameras. Then the crack width was assessed using the minimal crack edge detection technique. The proposed experimental results have accuracy as that of the measurement taken from the vernier caliper.

Sinha et al. [20] have investigated the cracks by using the two-step approach. They have developed a statistical filter design for the crack detection. After the filtering, they have got to the two-step approach at which the crack feature extraction was done locally at the first step of the pre-processing and then they have fused the images. The second step is to define the crack among the image segment by the process of cleaning and linking. They have overcome their previous work disadvantage where the morphological approach was used.

Talab et al. [22] have presented a new approach in image processing for detecting cracks in images of concrete structures. Here the methodology involves three steps: First; change the image to a gray image using the edge of the image and then use Sobel's method to develop an image using Sobel's filter for detecting cracks. Then by using suitable threshold binary image of the pixel they are categorized into the foreground and the background image. Once the images are categorized, Sobel's filtering was used for the elimination of residual noise. After the vast filtering procedure of the image, cracks were detected using the otsu's method. They have replaced the sober filter with the multiple median filtering in certain cases. Yamaguchi et al. [27] have developed a percolation-based crack detection technique. They have obtained their less computation time by the adaptation of the termination and skip add procedures. They have a high-speed percolation algorithm which will make use of the neighboring pixels based upon the circularity of the pixel needs. The template matching technique was the key to their proposal of percolation because matching in the percolation images was easy to analyze.

Yang et al. [28] have proposed an image analysis method to capture thin cracks and minimize the requirement for pen marking in reinforced concrete structural tests. They have used the studies like crack depth prediction [54], change in detection without image registration [54], crack pattern recognition based on artificial neural networks [55], applications to micro-cracks of rocks [56], and efficient sub-pixel width measurement [57]. Stereo triangulation method was the adopted technique based on cylinder formula approximation and image rectification. Once they have the rectified output, the surface of the observed regions can be unfolded and presented in a plane image for following displacement and deformation analysis. From which the crack detection was analyzed.

Zou et al. [30] have developed a fully automatic method to detect crack the pavement images. They used geodesic shadow removal algorithm to remove the pavement shadows by preserving the crack. After shadow removal, using the tensor voting methods crack probability map was built. Then by mapping crack probability map were represented by a graph model. Once the model was represented, Minimum Spanning Trees were derived from which the crack extraction data can be taken off by conducting recursive tree-edge pruning.

Oliveira et al. [32] have designed a system for the automatic crack detection. Here the crack detection was based on the sample paradigm. In the sample paradigm, a subset of the available image database was automatically selected and used for unsupervised training of the system images. They have characterized operations based on the classification of the non-overlapping image blocks. Then based on the crack block based detection, the width of the crack was estimated. They have proposed their system following the guidelines offered by the Portuguese Distress Catalogue [58].

Nguyen et al. [33] have proposed a method based on the edge detection of concrete cracks from noisy 2D images of concrete surfaces. They have observed the cracks as tree-like topology. Then based on the PSCEF non-crack objects were removed. After the separation, thresholding filter, and morphological thinning algorithm have been used to binarize the image for the crack centre line estimation. Then the centre line was fitted by cubic splines. They have linked the edge points to form the desired continuous crack edge. From the crack edge, the surface of the crack was attained.

Lins et al. [37] have developed a system based machine vision concepts with the goal to automate the crack measurement process. In their method, they have used only a single camera for the processing of the sequence of the images for the crack dimension estimation. The crack model algorithm HSB and RSV were used by which the sequences of the images are subjected to crack detection algorithm in order to detect the crack. The proposed algorithm receives images as inputs

Please cite this article in press as: A. Mohan, S. Poobal, Crack detection using image processing: A critical review and analysis, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2017.01.020

and outputs a new image with red particles along the detected crack. The pixel positions of the particles were stored in a vector and passed along to the crack measurement algorithm. With the pixel positions, the algorithm estimates the number of pixels in a cross section and outputs the crack dimension. Li et al. [38] have incorporated a new approach for detecting the crack in the defects with the dark color and the low contrast using the fast discrete curvelet waveform and texture analysis. They have initially decomposed and reconstructed the original image using the FDCT algorithm. Then the thresholds of the decomposition coefficients were calculated by the texture feature measurements, from which the surface textures in the images were eliminated. Finally, by extracting the contours from the reconstructed images, the expected image without texture but with crack defect contours was obtained.

Lee et al. [39] have designed a system for particle crack detection. They used the nearest neighbor and two-point correlation methods for the estimation of the second order microstructural descriptors. Based on the probability function of their corresponding location the crack features were found out. The edge effect was eliminated by the nearest neighbor estimate from the high-resolution montages.

Wang et al. [40] have proposed a system for the image based crack detection and to characterize the crack based upon their effectiveness. They have categorized the present image based crack detection into four categories. They are an integrated algorithm, morphological approach, percolation approach and practical technique. A shading correction was done using integrated algorithm. The unclear crack prediction was detected using percolation method. The crack detection was done using morphological approach for the micro crack detection with the practical method providing high-performance feature extraction.

Jahanshahi et al. [42] have proposed a method as an alternative to current monitoring method. They have proposed a less time-consuming method. They used an autonomous robotic system with vision based crack detection methodology for the processing of the 2D images. The depth parameters were adjusted automatically by the autonomous system. Then by using the 3D reconstruction technique, depth perception was obtained. The depth perception was obtained using 3D scene reconstruction. Their system was appropriate because they extract the whole crack from its background.

Hamrat et al. [45] have proposed an experimental work on the flexural behaviour of three types of concrete: normal strength concrete (NSC), high strength concrete (HSC) and high strength fiber concrete (HSFC) in terms of crack detection, crack development, crack width measurements and strain components, using the Digital Image Correlation (DIC) technique. They have used the classical measurement techniques (strain gauges, LVDT sensors) and the DIC technique for the analysis of strain components. The mutual understanding between the two measurement methods indicates DIC as an efficient measuring tool for obtaining displacement. Measurements of strains and displacements at or close to failure are usually not possible with the classical methods due to the risk involved in terms of safety to the personnel and damage to the equipment. They reduce both the crack spacing and the crack width by as much as 35–70% in mm as considered as an error.

Gunkel et al. [47] have developed a detection algorithm for the accuracy over the variability of the crack numbers and crack lengths over the similar image. The micro crack was detected using the shortest path algorithm in a situation where the cracks are surrounded by deformations. They have initially detected the crack clusters with a threshold value. Then the Dijkstra's algorithm was used to determine the crack paths. The linear paths of the linked path were determined by their algorithm.

Fujita et al. [48] have proposed a system for automatic crack detection on the noisy concrete surface mages. Their system includes two pre-processing steps and two detection steps. Only the original image was used for the pre-processing. They have removed the shadings using the median filtering. A multiscale line filter with the Hessian matrix was used to emphasize the cracks. After pre-processing, they have detected the crack coarsely without noise by a probabilistic method. They detected the crack more finely using an adaptive threshold algorithm. Glud et al. [49] have proposed an automated method for counting propagating matrix tunneling cracks for use in mechanical testing of GFRP laminates under different loading conditions. In [49], white light images were captured from specimens during the loading. The transmitted light was used to detect the cracks in the images, which were then processed to count the cracks as they develop and grow through the duration of the test. The reproducibility and accuracy of the image processing were demonstrated using simulated transverse crack densities and patterns.

3.2. IR-based image processing techniques

This section shows the IR image based processing technique, which is used in the process of crack detection. Rodríguez-Martín et al. [2] have proposed an Infrared (IR) thermography method based on IR image rectification with the extraction of Isotherms which allows the detection of cracks as well as the geometric characterization and orientation of the crack to assist the prediction of the direction of propagation of the crack through the material. It allows the fast and simple assessment of the morphology of different cracks (toe crack and longitudinal crack). The application of analysis with IR camera and subsequent image rectification which was used in their proposal allows the geometric characterization of the defects facilitating their classification according to the standards [59,60]. The detection of the crack using the notches in the irregularities was proposed by Broberg et al. [9]. Here using the IR thermography image rectification technique, they have detected based on notches which will differ depending on the temperature.

Brooks et al. [10] have proposed a contactless, non-invasive and non-destructive method for crack detection. They have used the thermal camera for detecting the reflection of an IR source from the surface of the crack. The proposed system [10] uses the specular reflection to identify the presence of any crack defects. Then they isolate the crack based on the position and the geometry of the reference surface. They have their results similar to that of the rapid real-time data acquisition. Pei et al. [15] have designed a new laser excited thermography technique with using laser spot array source. The difference between this proposals compared to the other IR based crack detection technique was that the source used here is the Laser. Here instead of imaging a crack by scanning a single laser spot, super-imposing the local discontinuity images with the present laser excited thermography methods were used. This proposed method also uses the Finite element method (FEM) for characterizing the effect of the crack geometry on the thermal images. The proposed method was based on the gradient of the thermal images for crack measurement with the laser spot array thermography.

Moreover, the use of the IR for the imaging, the change in the algorithm used can also be an adaptation of the crack detection procedure. Xu et al. [26] have proposed a system on infrared thermal image processing frame work based on superpixel to detect the crack. The segmentation was done based on the Fuzzy c-means clustering. The generation of the superpixels has been done because of its adherence to crack boundaries. The super pixels were selected from the raw gray image as well as high pass filtered image.

Guo et al. [46] have presented a methodology for the use of ultrasonic IR thermography for the crack detection. They have used optically-stimulated IR thermography for the effective crack detection. The processing tool used here for the analysis were PCA and Pulse phase thermography which is nothing but the convenient wavelet transform technique which is purported to be more noise resistant than the Fourier magnitude.

Rodríguez-Martín et al. [3] have proposed a methodology based on the analysis of the relationship between infrared (IR) data acquired with an infrared camera and geometric data into the crack extracted by applying a novel 3D macro-photogrammetric procedure. The 3D geometrical model is segmented into different sections, and the depth profiles were correlated with the different temperature values along the corresponding sections. The proposed techniques have obtained a correlation between depth data and thermal surface data. It will allow the design of a depth prediction model which enables the inspection of the depth of cracks using the thermography technique. In their proposed design, applied macro-photogrammetric procedure allows the generation of a 3D model of the crack in order to extract the depth data through the different sections and the application of a photogrammetric rectification algorithm to the infrared images allows the scaling of the images in order to provide the correspondence between thermal data and macro-photogrammetric depth data in the same dimension for each section.

3.3. Ultrasonic image based processing techniques

The crack detection in the Engineering structures upon the ultrasonic image processing technique is reviewed in this section.

Dhital et al. [11] have proposed a UPI system uses laser ultrasonic scanning excitation and piezoelectric air-coupled sensing technique. The UFT and WUPI algorithm were used to extract damage features based upon which the through diagnosis of the damage was performed. The proposed algorithm diagnosis [11] helps in finding the crack based on the extracted crack features. Methodologies [11] have a hybrid system to detect the crack with 96% accuracy.

In addition to the ultrasonic imaging system, ultrasonic sound can also be used to detect the surface crack with conceptual crack feature extraction.

Pascale et al. [16] have presented an ultrasonic based processed technique concerned at improving the application of the ultrasound method to the detection of crack depth. The results obtained have allowed providing useful information about the severity of the damage. The depth was estimated with good reliability for some of the most evident cracks presented in the sample. The maximum depth was evaluated at approximately 20 mm. By using this technique, the cracks due to the surface deterioration or diffusion have been detected. The TOFD technique serves the key here for the crack detection which was usually measured using the ultrasonic test. Depending upon the different TOF values measured on the crack zone as well as the crack free zone, the depth height h was estimated. The time of flight (TOF) and the attenuation (A) of the waves were usually measured in ultrasonic tests, but only the TOF was used when the aim was to estimate crack depth.

Shirahata et al. [18] have proposed a methodology that aims at discriminating between fatigue cracks by the ultrasonic non-destructive test. They have developed a tandem array ultrasonic testing systems that could detect the incomplete penetration. The transducer used for the tandem array could detect the reflected wave at the incomplete penetration and the bottom of the irregularity structure (Crack origin). The multi synthetic aperture focusing technique image reconstruction system was developed [18] to observe the crack tip closure and the opening which are remarkable for the longer cracks.

Wolf et al. [24] have presented a detection system to find the propagating cracks within the concrete structure using the sensitivity of the embedded ultrasonic sensors before it is visible on the surface of the concrete. They have used the sensitivity as a factor because of the sensors constant coupling to the medium, highly sensitive data analysis techniques, such as the correlation between signals and their attenuation, are applied to detect changes in the signal due to propagating cracks. The embedded ultrasonic sensor was used to monitor concrete elements regarding developing major cracks in the vicinity of the transmitted ultrasonic waves. The accuracy of the detected onset of the crack was evaluated with the non-destructive testing methods like acoustic emission and Digital Image Correlation [24]. Iliopoulos et al. [43] have proposed a method for crack detection by simultaneously applying Digital Image Correlation, Acoustic Emission, and Ultrasonic Pulse Velocity technique. The results of the employed techniques highlight the time and location of the crack. They have emphasized the severity of the cracks using the AE analysis. The image processing was done using matrix detection scheme because it can cross over the gray image with the original image. Kabir et al. proposed a detection system based on the GLCM texture analysis approach and ANN classifier. They have obtained the surface damage information such as total amount of superficial cracking, width, and length using ANN classifier. These methods were applied to thermographic, visual color and gray scale images of concrete blocks. Their results show imagery were effective with accuracy ranging from 71 to 75.2%.

Ganpatye et al. [50] have developed a detection matrix for the detection on the ultrasonic testing. Initially, the ultrasonic data were taken over the specimen. Then the data were corroborated with the results obtained using the tradition conventional methods like optical microscopy. Their results show excellent correlation between the comparisons. Using the ultrasonic back scattering technique, they have found the matrix cracks which are not optical images as in photography instead those are grey-scale representation.

Please cite this article in press as: A. Mohan, S. Poobal, Crack detection using image processing: A critical review and analysis, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2017.01.020

3.4. Laser image based processing technique

The detection of the cracks in the structures by using the Laser image in the image processing technique is reviewed in this section.

MostafaRabah et al. [13] have proposed a crack detection system with a high spatial resolution of imaging and the excellent capability of measuring the 3D space by laser scanning. The proposed design is of higher potential because of the combined action of the data acquisition and data compilation. The cracks detection and mapping was achieved by three steps, shading correction, crack detection and crack mapping. They have defined the crack in a pixel coordinate system. Once the definition was completed, a reverse engineering to remap the crack into the referred coordinate system was done. This was achieved by a hybrid concept of terrestrial laser-scanner point clouds and the corresponding camera image, i.e. a conversion from the pixel coordinate system to the terrestrial laser-scanner or global coordinate system. The results of their experiment show that the mean differences between terrestrial laser scan and the total station were about 30.5, 16.4 and 14.3 mms in x, y and z direction, respectively.

Sun et al. [21] have developed a 3-D crack detection technique based on laser. The sparse representation was developed to decompose profile signal into the summation of the cracks and main profile (MP). They have constructed a mixed dictionary, once the cracks were characterized. Mixed dictionary was constructed with an over complete exponential function and over complete trapezoidal membership function. They have compared the sparse representation using a matching pursuit algorithm. The effectiveness of the comparison was verified by the wavelet and median filtering method. In order to verify the effectiveness of their method, they constructed a simulation signal of main profile.

However the use of the Laser as a source might get involved in the crack discrimination. Nazaryan et al. [34] have developed a new method for the crack detection on the finished surfaces using the measurement technique. They have used the centroid method as a mathematical algorithm for the calculation of the crack features. Their results [34] showed a good correlation between calculated values. The attractive result of their investigation was due to the CCD technology and laser beam adapted.

3.5. TOFD image based processing techniques

The Time of Flight Diffraction image used in the image analysis of the crack detection is reviewed in this section. The TOFD is based on the Time of diffraction technique in which the scattered images are exploited with the cross-sectional imaging technique.

Merazi-Meksen et al. [1] have described a method of the sparse matrix replacing the image formation. In their type of imaging, a set of hyperbolas were used to correspond the crack tip positions. The hyperbolas were generated by applying the randomized Hough transform on the sparse matrix elements. The enhancement in signal to noise ratio was provided by the split spectrum processing. They analyze the curve formed by the sparse matrix elements to automate the crack detection.

Merazi-Meksen et al. [36] have proposed a methodology for the automation of the ultrasonic image interpretation using the NDT technique called the Time of Diffraction technique which aid in decision making. They have extracted the relevant pixels using the mathematical morphology approach corresponding to the presence of the discontinuities. Then the discontinuities were characterized using a pattern recognition technique. The region of interest was exploited using the watershed technique. They have used an erosion process for the image background removal, thereby improving the detection of the connected shapes present in the image. Skeletonization technique was adapted to reduce the remaining shapes as curves. The randomized Hough transform was used for the crack detection in those curves.

3.6. Various other types of image-based processing techniques

3.6.1. Electroluminescence image

Electroluminescence (EL) is an optoelectrical phenomenon. When electrocuted, the specimen emits light in response to the passage of an electric current and is imaged using EL camera. This is completely different from the black body light emission. EL technique is used for the visualization like the high-resolution cameras.

Anwar et al. [8] have presented a system for micro crack detection in the crystalline structure. The presence of the various types of the image anomalies like dislocation clusters, grain boundaries and discontinuities in the gray levels makes the micro crack detection very challenging. In their work, an anisotropic diffusion filtering algorithm was used. The filtering technique was able to enhance the pixel levels. Their results show an accuracy averaging from 90%.

3.6.2. UAV camera image

Aiming at the use of Unmanned Aerial Vehicle (UAV) in civil construction for autonomous inspection of building pathologies provides an essential task in maintaining a safe operation. But it is expensive as well. Automation of crack detection process may result in great monetary savings and can lead to more frequent inspection cycles. Motivated by recent developments and an increasing availability of UAVs (Unmanned Aerial Vehicle) a growing number of applications have been developed over the last years, ranging from inspections of transmission lines, monitoring of fractionation towers in refineries. The image taken by the UAV camera is of varying features from the commercial camera image due to its nigh image quality and multi-disciplinary nature.

Pereira et al. [14] have proposed an Unmanned Aerial Vehicle (UAV) in civil construction for autonomous inspection of building pathologies with some alternatives of image processing algorithm for the crack detection in the building structures. These algorithms should run in an embedded computing platform installed on UAVs. They have used two image processing algorithms for crack detection. Their first algorithm uses edge detection based on the Sobel operator or Sobel filter [SOBEL 1990]. The Sober filter is a discrete differentiation operator. At each point in the image, the result of the Sobel operator was either the corresponding gradient vector or the norm of this vector. Their second selected algorithm was a nonparametric filter based on Bayes algorithm, the Particle Filter [THRUN 2006]. The particle filter seeks to relate the probability of an image segment to be characterized or not by a crack, based on pixel intensity and the number of pixels in its neighborhood.

3.6.3. SEM image

Scanning Electron Microscopy (SEM) is one of the primary methods used to inspect a wide range of materials, including metallic coatings. It uses a beam of high-energy electrons to generate a variety of the signals at the surface of the specimen. The signal from the electron intervention gives useful information about the morphology (texture), composition, etc.

Vidal et al. [23] have proposed a system on SEM images for the crack detection. They have binarized the SEM images using proper threshold from the histogram of images, once they have been filtered from nodules and background. The aim of their work was to binarize SEM images to distinguish cracks from the background (the rest of the image). Their method uses the second derivative of the histogram obtained with the Laplacian of Gaussian (LoG), together with Prewitt vertical edge detector for the quantification of the spatial cracked area with much more accuracy. In order to compare different SEM images, the intensity values were firstly adjusted so that the image's contrast was analogous for all of them. Afterward, some techniques to specifically enhance and segment the cracks from the overall were tried, and finally quantification of the cracks was made by computation of segmented pixels.

3.6.4. Probe image

Microscope probe is a microscope capable of color imaging with high resolution. The spatial resolution of the probe image is ranging from infinity imaging down to 3 μm per pixel. In support of robotic field investigations, probe imaging and context imaging with high operation flexibility is adopted.

Chen et al. [35] have developed a load differential method. They have evaluated the crack detection with the load dependence of the crack openings. The load differential method was adapted because it compares the guided wave signals with recorded damage free data. They have demonstrated with the help of a sparse array of piezoelectric transducers on an aluminum plate specimen. The delay-and-sum imaging algorithm was used to visualize the opening effects on the cracks due to increasing tensile loads.

3.6.5. Sensor image

Sensor senses the concerned criteria and sends the information. Similarly, the imaging sensor is a sensor that detects and convoys the information that constitutes an image. The information retrieved as a small burst of current is by using attenuation of the waves into the signals. The waves can be light or other electromagnetic radiation.

Heideklang et al. [44] have proposed a methodology for improving the detection of near-surface defects in magnetizable and conductive specimens by combining the measurements of eddy current, magnetic flux leakage and thermography testing. Different signal processing methods for data normalization were proposed to enable data fusion at the pixel level. They have applied the stated pixel-wise and multi-scale data fusion strategies. They have proposed methods for signal normalization to facilitate signal-level fusion of independent NDT imagery results. Then they have fused the signal normalization results with simple algebraic fusion rules.

3.6.6. Radar image

The radar image is similar to that of a flash camera image which provides its light to illuminate an area on the ground to take a snapshot picture, but at radio wavelengths. The radar uses an antenna and digital computer tapes to record its images. Imaging radar is an application of radar used to create two-dimensional images. The images of radar are composed of many dots. Each pixel represents the radar backscatter of the area on the ground imaged. Brighter areas represent high backscatter and darker represents low scatter.

Agarwal et al. [19] have designed a millimeter wave based non-invasive crack detection of packaged ceramic tiles using an ingeniously designed V-band (60 GHz) imaging radar system. Their main consideration was to detect crack with the minimal false alarm. It was achieved by adopting a Statistics-based adaptive algorithm. Crack detection algorithm was developed with the combined activity of the mathematical formation and multi-objective generic algorithm optimization.

3.6.7. Microwave image

Microwave imaging is a technique adapted evolved from the radar techniques. It uses electromagnetic waves in microwave regime (i.e., ∼300 MHz–300 GHz) to detect the hidden or embedded objects in as structure (or media). They are of either quantitative or qualitative type. The parameter evaluation is done by solving a nonlinear inverse problem so called as inverse scattering method.

Oliveri et al. [31] have proposed a framework for microwave imaging as a better replacement for the existing nondestructive testing and evaluation techniques (NDT/NDE) [61]. They do not need direct physical contact with the associated sensors. They have used an innovative 3-D imaging technique to detect the cracks in the anisotropic media. Their 3-D imaging uses 3-D MOM matrices combined with the compressive sensing solver based on the Bayesian to retrieve the unknown equivalent currents corresponding to sparse crack profile.

3.6.8. Video image

This section investigates about the video image based processing technique. In this criteria, video segment data are subjected to process for the crack detection.

Xue-jun et al. [25] have developed a crack detection method on reinforced concrete bridge based on the performance assessment with the digital image technology. They have analyzed the effects of the gray level image, pixel rate, noise filter and edge detection. The edge identification was done using the Harris method and the SV method. They have developed a Visual C++6.0 program to detect the cracks. They have tested 15 cases of bridge video image, and their result indicates that the relative error was within 6% for cracks larger than 0.3 mm cracks and less than 10% for the crack width between 0.2 mm and 0.3 mm.

Please cite this article in press as: A. Mohan, S. Poobal, Crack detection using image processing: A critical review and analysis, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2017.01.020

4. Analysis and discussion

This section shows the analysis of crack detection based on the literature taken for reviewing, in which we have considered various factors for analysis, such as objective based analysis, accuracy level based analysis, error level based analysis and the image processing techniques based analysis.

4.1. Objective based analysis

In this section, Fig. 2 shows the bar chart representing the objective based analysis of the crack detection criteria which is considered reviewing. The objective of crack detection may be of many types depending on the parameter with which the crack detection is made possible. Some of the objective which makes this analysis possible: length, width, depth, position, surface and direction of propagation of the crack. Many proposals are compromising the crack detection with the surface detection of the crack as a concerned factor since the surface estimates the volume of the crack. From the above reviewed 50 papers, the objective of the surface of the crack was obtained by 22 papers. The objective of the position of the crack was attained by [10]. Moreover papers [1,4,50,30,28,22] reached the objective of the length of the crack. In addition to the length, width was also obtained as an objective by [3,37,41]. Then the width of the crack was obtained in 6 of the papers reviewed. From the reviewed paper, we attain a conclusion that most of the methodologies objective was the surface of the crack.

4.2. Data set based analysis

In this section, Fig. 3 shows the analysis based on the datasets utilized by the various systems reviewed. The different types of the datasets used here are a Real data set, TAMU data set, BYTEC data set, USNF data set, GRAI data set, POSCO data set, LAWP data set, SURFCOAT data set, CRST data set, TITS data set, NSFC data set, etc. Accordingly, many of the papers like [2,3,5,6,12,16–18,22,26,35,36,38,40,46–49] have used the real data set of their experimental setup. The locally available images were used as the dataset in [1,4,9,10,15,21,33,34,36]. Some of the data set like CNRS, LAWP, TITS and TAMU were utilized in the papers

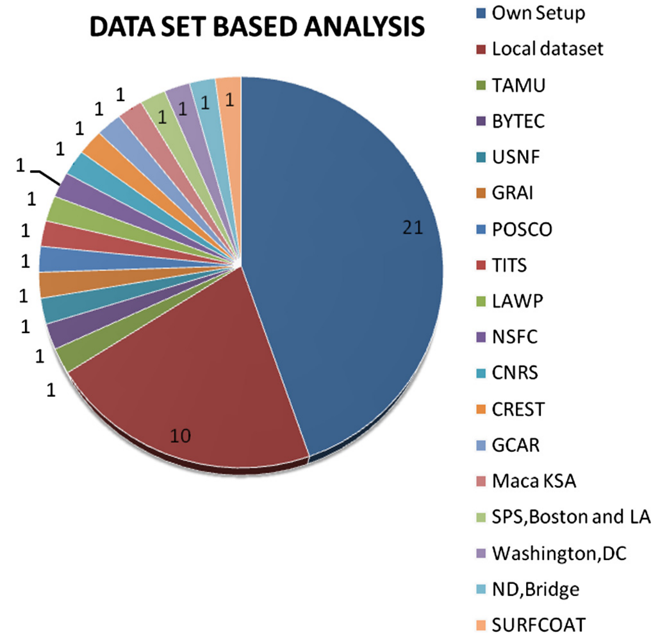

Fig. 3 Pie chart for the data set based analysis.

[29,30,32,50] respectively. Finally, we can conclude that the more number of papers have used real dataset for the detection of crack.

4.3. Accuracy level based analysis

In this section, Table 1 shows the accuracy based analysis of the papers taken from the literature survey. Here, the reviewed papers are categorized into 6 types based on the level of the accuracy as below 70%, 70–75%, 80–85%, 85–90%, 90–95% and above 95%. Here, the papers [12,21,32,40] have attained accuracy level more than 90%. Similar accuracy of about 90–95% were achieved by [2,11,17,25,30,37,38,48] respectively.

4.4. Error level based analysis

In this section, Table 2 shows the error level based analysis of the reviewed papers. Here the error level is mentioned in the

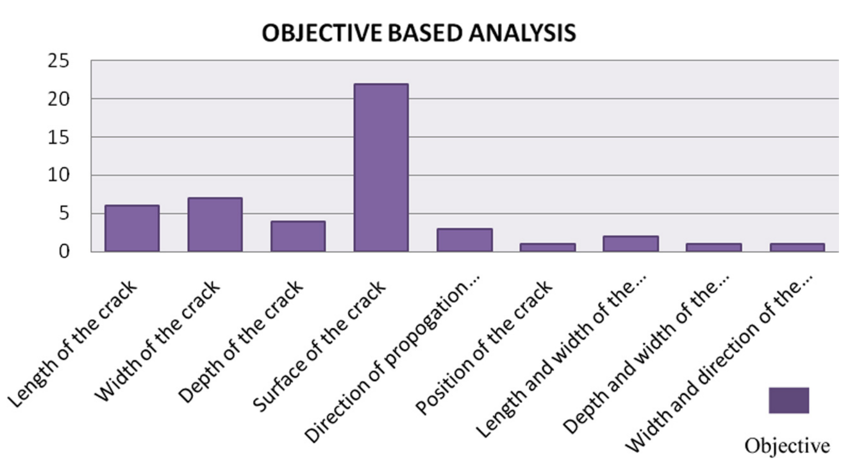

Fig. 2 Bar chart based on the objective.

Table 1 Analysis based on accuracy level.

Accuracy level	Papers
Below 70%	[9,10,24,16]
70–75%	[41]
80–85%	[46,49,50]
85–90%	[8,39]
90–95%	[2,11,17,25,30,37,38,48]
Above 95%	[12,21,32,40]

Table 2 Analysis based on error level.

Error level	Papers
0.0038	[3]
0.1–0.3	[13]
1.20	[34]

level of deviation of the width of the crack not detected. The error level tends to rise due to the in accurate map result when the crack extracted values mismatch with the compared result values. Here the paper [13] is adhered to an error level from 0.1 to 0.3. The paper [34] reached an error of about 1.20 respectively.

4.5. Image processing techniques based analysis

In this section, Table 3 shows the analysis of the reviewed papers on the image processing techniques used for the crack detection in the engineering structures. Morphological approach was used by many of the proposed methodologies including [9,20,36,42] and [40]. The collection of non-linear operations (such as erosion, dilation, opening, closing, top-hat filtering, and watershed transform) associated with the shape or features in an image is referred as a morphological approach. Some of the systems have used wavelet transform as a better processing technique because of its efficiency. The wavelet transformation is the most important technique for the time-frequency-transformations. Moreover, the wavelet transform is alike to the Fourier transform with a completely different merit function. They were [11,23,38,46] respectively. Some proposals [6,10,43,45] used Correlation technique by the merging of the images using the DIC techniques. The Digital Image Correlation (DIC) is a full-field image scrutiny method, by gray value digital images, that can decide the contour and the displacements of an object under load in three dimensions. For the reduced image based analysis Randomized Hough transform was used as a better replacement in [1,23]. The Randomized Hough transforms are the methods for object detection, a critical step in many implementations of computer vision. Specially, the Randomized Hough transform is a probabilistic variant to the classical Hough transform, and it is used to detect curves. For the easier segmentation at the pre-processing level techniques like threshold method, otsu's method, superpixel algorithm was employed in [22,49,6,47,48,26]. Here, the Otsu's method is used to perform clustering-based image thresholding automatically and the statistical approach is the collection, analysis, interpretation, presentation, and organization of data. Some of the detection was majorly based on the texture analysis technique as used in [38,41]. Moreover, data fusion filtering in [8,44] is the fusion of data from noisy sensors to improve the estimation of the present value of state variable of a system. The skeletonization in [5,36] is to extract a region-based shape feature representing the general form of an object. The GLCM Texture analysis in [38,41] is used to extract second order statistical texture features for motion estimation. In Photogrammetry [4,8] is the science of making measurements from photographs, especially for recovering the exact positions of surface points. The Photo acoustic imaging [6,11] is a biomedical imaging modality based on the photo acoustic effect. In photoacoustic imaging, non-ionizing laser pulses are delivered into biological tissues. Finally, the analysis based on the image processing techniques reviews the fact that improved processing techniques were introduced only in the post-processing.

Table 3 Analysis based on image processing techniques.

Image processing techniques	Papers
Morphological approach	[9,20,36,42,40]
Digital image correlation	[6,10,43,45]
Randomized hough transform	[1,23]
Ultrasonic pulse velocity technique	[24,43]
Wavelet transform	[11,23,38,46]
Median filtering	[23,48]
Gabor filtering	[49]
Otsu's method	[22,49]
Statistical approach	[19,20]
Threshold method	[6,47,48]
Superpixel algorithm	[26]
Data fusion filtering	[8,44]
Reconstruction technique	[3,8,42]
Photogrammatic technique	[4,8]
PA imaging	[6,11]
Percolation	[27,40]
Centroid method	[34]
Delaying and summing algorithm	[35]
GLCM texture analysis	[38,41]
Dijkstra's algorithm	[49]
Skeletonization techniques	[5,36]

4.6. IP-based crack detection for safety monitoring

More number of recent research works has been done in the crack detection system for the safety issues, as safety has become a major concern in every applications. Basically, Image processing is the most common method to detect a crack in a safety way. In [62], the automatic crack detection for subway tunnel has been performed for safety monitoring. Here, the image processing techniques have been used to monitoring the subway tunnels. Moreover, image-based reconstruction for automated crack detection and digital crack measurements were implemented in [63]. In addition, the Pavement crack detection has adopted in order to detect cracks effectively and accurately in [65]. Here, pavement crack image processing algorithm has adopted to eliminate the isolated noise point, smooth the edge and enhance the segmentation accuracy in a safety way. Further, the crack information has obtained in a secure manner through morphological expansion corrosion in [64].

Please cite this article in press as: A. Mohan, S. Poobal, Crack detection using image processing: A critical review and analysis, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2017.01.020

5. Gaps and issues

Based on the literature review conducted, we identify some of the short comings in the detection procedure which need more sophistication for the error free future work. Some of the challenges are discussed below:

The directions of propagation of the cracks are crucial to detecting. The limitation of the [2] is that the measurement in the transversal direction does not present enough accuracy compared with the longitudinal measures of the crack depth. Normally, for analyzing the propagation of crack, the longitudinal direction is more representative that transversal direction, but the mentioned difference of actuary between the two directions could be a problem when the inspector intends to measure the width or when the objective of application of technique is to establish the relationship between width and longitude of the crack [2].

It is impossible to predict the depth of the open surface cracks based on the sequence of the images with different materials and topologies using thermography. So NDT thermography with better algorithm might get organized to overcome the irregularities at the accuracy and efficiency. The algorithm used in [7] is poor because some of the quality measures such as completeness may out weight others due to the application and urgency [7]. As discussed in [47], one path appropriation for the description of the crack is available. So for cracks like a tree, it is difficult to consider. So the system must be extended with an improved appropriation to find all the branches of the crack tree.

An autonomous system which can quantify, locate and classify different crack types and manage huge amount of data's collected is an essential one for automatic crack detection. So robust decision-making tools must be developed to allow fast analysis of the risk of every crack to fill the gap between the detecting cracks and helping asset managers to take action immediately [42]. The image type used may also affect the system. For the camera image based detection, the low resolution of the image is a factor for mislead [37]. For the exceptional result, the crack detection must be employed with the global information sharing for the image with the enhanced image resolution and combining them with other algorithms, adopting more realistically [25].

In [17], the stereo vision based detection system is used. The accuracy of this system completely depends on the effect of the lighting condition. So it must be taken into account for.

The main difficulty in the ultrasonic investigation such as the irregularity of the surface, the inability to use the coupling materials normally used, and the presence of contact between the edges of the crack must be well assessed [6]. The existing algorithm in [2] must have a superior plan for the post processing technique because of the limitation in analyzing the connected components. Results reported in [12] on concentrate pavement images with high levels of surface texture that make crack detection difficult must be sharpened with better texture analysis procedure [12].

6. Conclusion

This paper provides the collective survey of the different image processing techniques used for the detection of the cracks in the engineering structures. The main intention of this study was about to study and review the crack detection system based on image processing. Here we have taken 50 research papers for the review based on the crack detection. We have finalized our review based on the analysis of the five features. The first one is objective based analysis on to which the objectives like the length of the crack, width of the crack, direction of propagation of the crack are considered. Secondly, the datasets utilized for the methodologies were analyzed upon which we conclude that most of the system uses real data sets for the convenience as well as efficiency. Next, the analyses based on the accuracy level as well as the error level in some cases are scrutinized. Finally, we have performed the analysis based on the image processing techniques used in each system. And also we present the research issues which can be useful for the further research on the image processing based crack detection system. Based on the analysis, we conclude that more number of researchers have used the camera type image for the analysis with better segmentation algorithm like threshold technique and reconstructable feature extraction technique for the thorough damage analysis. In the future, we plan to conduct a survey on the different techniques available for invasive method-based crack detection as this works presents an extensive study over the noninvasive methods of crack detection.

References

[1] Thouraya Merazi Meksen, Bachir Boudra, Redouane Drai, Malika Boudraa, Automatic crack detection and characterization during ultrasonic inspection, J. Nondestr. Eval. 29 (3) (2010) 169–174.

[2] M. Rodríguez-Martína, S. Lagüelaa, D. González-Aguileraa, J. Martínezb, Thermographic test for the geometric characterization of cracks in welding using IR image rectification, Autom. Constr. 61 (2016) 58–65.

[3] M. Rodríguez-Martína, S. Lagüelaa, D. González-Aguileraa, J. Martinezb, Prediction of depth model for cracks in steel using infrared thermography, Infrared Phys. Technol. 71 (2015) 592–600.

[4] Zhang Yiyang. The design of glass crack detection system based on image pre-processing technology, in: Proceedings of Information Technology and Artificial Intelligence Conference, 2014, pp. 39–42.

[5] R.S. Adhikari, O. Moselhi1, A. Bagchi, Image-based retrieval of concrete crack properties for bridge inspection, Autom. Constr. 39 (2014) 180–194.

[6] S.Y. Alam, A. Loukili, F. Grondin, E. Rozière, Use of the digital image correlation and acoustic emission technique to study the effect of structural size on cracking of reinforced concrete, Eng. Fract. Mech. 143 (2015) 17–31.

[7] Shivprakash Iyer, Sunil K. Sinha, A robust approach for automatic detection and segmentation of cracks in underground pipeline images, Image Vis. Comput. 23 (10) (2005) 931–933.

[8] Said Amirul Anwar, MohdZaid Abdullah, Micro-crack detection of multicrystalline solar cells featuring an improved anisotropic diffusion filter and image segmentation technique, EURASIP J. Image Video Process. 1 (2014).

[9] Patrik. Broberg, Surface crack detection in welds using thermography, NDT E Int. 57 (2013) 69–73.

[10] Will S.M. Brooks, Dan A. Lamb, Stuart J.C. Irvine, IR reflectance imaging for crystalline Si solar cell crack detection, IEEE J. Photovolt. 5 (5) (2015) 1271–1275.

[11] D. Dhital, J.R. Lee, A fully non-contact ultrasonic propagation imaging system for closed surface crack evaluation, Exp. Mech. 52 (8) (2012) 1111–1122.

Please cite this article in press as: A. Mohan, S. Poobal, Crack detection using image processing: A critical review and analysis, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2017.01.020

[12] M. Salman, S. Mathavan, K. Kamal, M. Rahman, Pavement crack detection using the gabor filter, in: Proceedings of 16th International IEEE Annual Conference on Intelligent Transportation Systems, 2013, pp. 2039–2044.
[13] Mostafa Rabaha, Ahmed Elhattab, Atef Fayad, Automatic concrete cracks detection and mapping of terrestrial laser scan data, NRIAG J. Astron. Geophys. 2 (2) (2013) 250–255.
[14] Fábio Celestino Pereira, Carlos Eduardo Pereira, Embedded image processing systems for automatic recognition of cracks using UAVs, IFAC-PapersOnLine 48 (10) (2015) 16–21.
[15] Cuixiang Pei, Jinxin Qiu, Haocheng Liu, Zhenmao Chen, Simulation of surface cracks measurement in first walls by laser spot array thermography, Fusion Eng. Des. (2015).
[16] Giovanni Pascale, Antonio Lolli, Crack assessment in marble sculptures using ultrasonic measurements: laboratory tests and application on the statue of David by Michelangelo, J. Cultural Herit. 16 (6) (2015) 813–821.
[17] Baohua Shan, Shijie Zheng, Jinping Ou, A stereovision-based crack width detection approach for concrete surface assessment, KSCE J. Civ. Eng. 20 (2) (2016) 803–812.
[18] Hiromi Shirahata, Chitoshi Miki, Ryota Yamaguchi, Kohji Kinoshita, Yasutoshi Yaginuma, Fatigue crack detection by the use of ultrasonic echo height change with crack tip opening, Weld. World 58 (5) (2014) 681–690.
[19] Smriti Agarwal, Dharmendra Singh, An adaptive statistical approach for non-destructive underline crack detection of ceramic tiles using millimetre wave imaging radar for industrial application, IEEE Sens. J. 15 (12) (2015) 7036–7044.
[20] Sunil K. Sinha, Paul W. Fieguth, Automated detection of cracks in buried concrete pipe images, Autom. Constr. 15 (1) (2006) 58–72.
[21] Xiaoming Sun, Jianping Huang, Wanyu Liu, Mantao Xu, Pavement crack characteristic detection based on sparse representation, EURASIP J. Adv. Signal Process. (2012).
[22] Ahmed Mahgoub Ahmed Talab, Zhangcan Huang, Fan Xi, Liu Hai Ming, Detection crack in image using Otsu method and multiple filtering in image processing techniques, Optik – Int. J. Light Electron Opt. 127 (3) (2016) 1030–1033.
[23] M. Vidal, M. Ostra, N. Imaz, E. García-Lecina, C. Ubide, Analysis of SEM digital images to quantify crack network pattern area in chromium electrodeposits, Surf. Coat. Technol. 285 (2016) 289–297.
[24] J. Wolf, S. Pirskawetz, A. Zang, Detection of crack propagation in concrete with embedded ultrasonic sensors, Eng. Fract. Mech. 146 (2015) 161–171.
[25] Xue-jun Xu, Xiao-ning Zhang, Crack detection of reinforced concrete bridge using video image, J. Cent. South Univ. 20 (9) (2013) 2605–2613.
[26] Changhang Xu, Jing Xie, Guoming Chen, Weiping Huang, An infrared thermal image processing framework based on superpixel algorithm to detect cracks on metal surface, Infrared Phys. Technol. 67 (2014) 266–272.
[27] Tomoyuki Yamaguchi, Shuji Hashimoto, Fast crack detection method for large-size concrete surface images using percolation-based image processing, Mach. Vis. Appl. 21 (5) (2010) 787–809.
[28] Yuan-Sen Yang, Chung-Ming Yang, Chang-Wei Huang, Thin crack observation in a reinforced concrete bridge pier test using image processing and analysis, Adv. Eng. Softw. 83 (2015) 99–108.
[29] J. Zakrzewski, N. Chigarev, V. Tournat, V. Gusev, Combined photoacoustic–acoustic technique for crack imaging, Int. J. Thermophys. 31 (1) (2010) 199–207.
[30] Qin Zou, Yu Cao, Qingquan Li, Qingzhou Mao, Song Wang, CrackTree: automatic crack detection from pavement images, Pattern Recogn. Lett. 33 (3) (2012) 227–238.
[31] Giacomo Oliveri, Ping-Ping Ding, Lorenzo Poli, 3-D crack detection in anisotropic layered media through a sparseness-regularized solver, IEEE Antennas Wirel. Propag. Lett. 14 (2015) 1031–1034.
[32] Henrique Oliveira, Paulo Lobato Correia, Automatic road crack detection and characterization, IEEE Trans. Intell. Transp. Syst. 14 (1) (2012) 155–168.
[33] Hoang-Nam Nguyen, Tai-Yan Kam, Pi-Ying Cheng, An automatic approach for accurate edge detection of concrete crack utilizing 2D geometric features of crack, J. Signal Process. Syst. 77 (3) (2014) 221–240.
[34] Nikolay Nazaryan, Claudio Campana, Saeid Moslehpour, Devdas Shetty, Application of a He–Ne infrared laser source for detection of geometrical dimensions of cracks and scratches on finished surfaces of metals, Opt. Lasers Eng. 51 (12) (2013) 1360–1367.
[35] Xin Chen, Jennifer E. Michaels, Sang Jun Lee, Thomas E. Michaels, Load-differential imaging for detection and localization of fatigue cracks using Lamb waves, NDT E Int. 51 (2012) 142–149.
[36] Thouraya Merazi-Meksen, Malika Boudraa, Bachir Boudraa, Mathematical morphology for TOFD image analysis and automatic crack detection, Ultrasonics 54 (6) (2014) 1642–1648.
[37] Romulo Gonçalves Lins, Sidney N. Givigi, Automatic crack detection and measurement based on image analysis, IEEE Trans. Instrum. Meas. 65 (3) (2016) 583–590.
[38] Xueqin Li, Honghai Jiang, Guofu Yin, Detection of surface crack defects on ferrite magnetic tile, NDT E Int. 62 (2014) 6–13.
[39] S.G. Lee, Y. Mao, A.M. Gokhaleb, J. Harris, M.F. Horstemeyer, Application of digital image processing for automatic detection and characterization of cracked constituent particles/inclusions in wrought aluminum alloys, Mater. Charact. 60 (9) (2009) 964–970.
[40] Pingrang Wang, Hongwei Huang, Comparison analysis on present image-based crack detection methods in concrete structures, in: Proceedings of 2010 3rd International Congress on Image and Signal Processing (CISP2010), vol. 5, 2010, pp. 2530–2533.
[41] Shahid Kabir, Imaging-based detection of AAR induced map-crack damage in concrete structure, NDT E Int. 43 (6) (2010) 461–469.
[42] Mohammad R. Jahanshahi, Sami F. Masri, Adaptive vision-based crack detection using 3D scene reconstruction for condition assessment of structures, Autom. Constr. 22 (2012) 567–576.
[43] S. Iliopoulos, D.G. Aggelis, L. Pyl, J. Vantomme, P. Van Marcke, E. Coppens, L. Areias, Detection and evaluation of cracks in the concrete buffer of the Belgian Nuclear Waste container using combined NDT techniques, Constr. Build. Mater. 78 (2015) 369–378.
[44] Rene Heideklang, Parisa Shokouhi, Multi-sensor imagefusion at signal level for improved near-surface crack detection, NDT E Int. 71 (2015) 16–22.
[45] M. Hamrat, B. Boulekbache, M. Chemrouk, S. Amziane, Flexural cracking behavior of normal strength, high strength and high strength fiber concrete beams, using Digital Image Correlation technique, Constr. Build. Mater. 106 (2016) 678–692.
[46] Xingwang Guo, Vladimir Vavilov, Crack detection in aluminum parts by using ultrasound-excited infrared thermography, Infrared Phys. Technol. 61 (2013) 149–156.
[47] Christina Gunkel, Alexander Stepper, Arne C. Müller, Christine H. Müller, Micro crack detection with Dijkstra's shortest path algorithm, Mach. Vis. Appl. 23 (3) (2012) 589–601.
[48] Yusuke Fujita, Yoshihiko Hamamoto, A robust automatic crack detection method from noisy concrete surfaces, Mach. Vis. Appl. 22 (2) (2011) 245–254.
[49] J.A. Glud, J.M. Dulieu-Barton, O.T. Thomsen, L.C.T. Overgaard, Automated counting of off-axis tunnelling

Please cite this article in press as: A. Mohan, S. Poobal, Crack detection using image processing: A critical review and analysis, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2017.01.020

cracksusing digital image processing, Compos. Sci. Technol. 125 (2016) 80–89.
[50] Vikram K. Kinra, Atul S. Ganpatye, Konstantin Maslov, Ultrasonic ply-by-ply detection of matrix cracks in laminated composites, J. Nondestr. Eval. 25 (1) (2006) 37–49.
[51] Bernard Budiansky, Richard J. O'connell, Elastic moduli of a cracked solid, Int. J. Solids Struct. 12 (2) (1976) 81–87.
[52] Jacob Aboudi, Stiffness reduction of cracked solids, Eng. Fract. Mech. 26 (5) (1987) 637–650.
[53] Online video Lectures by Prof. P.K. Biswas, IIT Kharagpur, Department of Electronics and communication engineering, <http:/nptel.iitm.ac.in/syllabus/syllabus.php?subjectid=117105079>.
[54] R.S. Adhikari, O. Moselhi Bagchi, Image-based retrieval of concrete crack properties for bridge inspection, Autom. Constr. 39 (2014) 180–194.
[55] B.Y. Lee, Y.Y. Kim, S.T. Yi, J.K. Kim, Automated image processing technique for detecting and analysing concrete surface cracks, Struct. Infrastruct. Eng 9 (6) (2013).
[56] A. Arena, C. DellePiane, J. Sarout, A new computational approach to cracks quantification from 2D image analysis: application to micro-cracks description in rocks, Comput. Geosci. 66 (2014) 106–120.
[57] H.N. Nguyen, T.Y. Kam, P.Y. Cheng, An automatic approach for accurate edge detection of concrete crack utilizing 2D geometric features of crack, J. Signal Process. Syst. (2013) 1–20.
[58] Catálogo de Degradações dos PavimentosRodoviáriosFlexíveis—2nd ver, JAE, Ex Junta Autónoma das Estradas, Almada, Portugal, 1997.
[59] Welding and allied processes—classification of geometric imperfections in metallic materials—Part 1: Fusion welding, European Committee for Standardization, EN-ISO 6520–1:2007, 2007.
[60] Welding. Fusion-Welded Joints in Steel, Nickel, Titanium and Their Alloys (Beam Welding Excluded). Quality Levels for Imperfections (ISO 5817:2003 corrected version. 2005, including Technical Corrigendum), European Committee for Standardization. EN-ISO-5817:2009, 2009.
[61] R. Miorelli, C. Reboud, D. Lesselier, T. Theodoulidis, Eddy current modeling of narrow cracks in planar-layered metal structures, IEEE Trans. Magn. 48 (10) (2012) 2551–2559.
[62] Wenyu Zhang, Zhenjiang Zhang, Dapeng Qi, Yun Liu, Automatic crack detection and classification method for subway tunnel safety monitoring, Sensors 14 (2014) 19307–19328.
[63] Paul Zheng, Cristopher D. Moen, Crack detection and measurement utilizing image-based reconstruction, Struct. Eng. Mater. (2014).
[64] Dapeng Qi1, Yun Liu1, Qingyi Gu, Fengxia Zheng, An algorithm to detect the crack in the tunnel based on the image processing, J. Comput. 26 (3) (2015).
[65] Z. Qingbo, Pavement crack detection algorithm based on image processing analysis, in: 8th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC), Hangzhou, China, 2016, pp. 15–18.