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A Comparative Review of Image Processing Based Crack Detection Techniques on Civil Engineering Structures

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ABSTRACT

Crack detection and repair of the cracks in engineering structures is essential to ensure serviceability and durability. Traditionally, cracks are detected by the examiner's visual inspection; as a result, crack detection and estimation of characteristics are greatly dependent on the examiner's personal judgment, which has aided in the repair of various structures and evaluation of the crack phenomenon in previous decades. Due to industrial advancement, the number of engineering structures has increased, but compared to that, expertise in the crack detection field did not raise that level. So, a less time-consuming and more accurate approach is needed. The image processing technique works simultaneously to detect the cracks with their attributes. In this context, the development of the algorithm and the implementation procedure is also simple. But some defects such as identifying noises as cracks and weakness in identifying micro-cracks have become significant challenges for this technique. Unable to locate transverse cracks in concrete structures is also a vital issue. So, to develop an accurate method, an extensive survey on the current articles is needed. In this paper, a critical analysis has been done on crack detection through the image processing phenomenon and a detailed literature review to understand the prospects of this method. From the literature review, it was observed that a general structure of CNN-based algorithm with camera images for crack detection could be an efficient approach with higher accuracy.

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1. Introduction

Cracks are a common phenomenon in engineering structures. Especially for concrete-based structures, cracks can occur due to cyclic load, fatigue stress and tensile stress. The cracks on engineering structures reduces the local stiffness and cause discontinuity of the materials [1]. Moreover, the generation of cracks and widening of it in the concrete structures decreases the lifetime of the structure and causes corrosion of the embedded rebar inside the concrete, which ultimately fails the structure. So, cracks in the concrete surface should be treated properly as surface cracks are critical indicators of structural damage [2]. Fortunately, early crack detection and prevention of cracks are possible, which prohibits financial losses and casualties.

Though, crack detection in the manual process, which is dependent on the personal justification and judgement of the specialists, has shown acceptable performance in the past decades. But it is mainly dependent on the experience of the examiner. With modern industrialization, as the number of structures has increased by a significant amount. So, an alternative and more exact detection process is needed [3].

Crack detection through image processing is a technique of surface crack detection that mainly uses image processing-based algorithms to differentiate cracks from engineering structures surfaces. Crack detection through image processing effectively analyzes and detects characteristics of cracks such as crack width, length and area [4]. So, automatic crack detection can be an alternative to manual procedures that possess more accuracy and reliability [5].

Image processing is a Non-destructive testing method that can be conducted by various technical approaches such as (i) Ultrasonic testing, (ii) Laser-based testing, (iii) Infrared and thermal testing and (iv) Radiographic testing [6]. Due to the simplicity and accuracy of image-based crack detection, the interest among researchers in developing more convenient techniques is increasing day by day. Recent studies on bridges, dams, and tall buildings also indicated that to enhance the structure's durability, an assessment of the accurate service life and present condition is needed. In this case, image-based assessment is more effective than traditional inspection [7].

Though image-based crack detection is a promising technique but some limitations of this technique, such as: counting surface noises as cracks, unable to detect the direction of the propagation of cracks properly, and limited practical use, has developed a big challenge for the researchers to overcome and establish a more proper and accurate technique. So, a deep study of the existing methodology is needed.

In this research study, an attempt has been taken to summarize various research findings based on crack detection through image processing to find out the existing pros and cons and analyze the future prospects of this technique in the field of Structural engineering.

2. Methodology

This paper was conducted by analyzing the various published research articles depending on the method followed for image processing and the significant outcomes obtained in the research by analyzing the key information of the published articles. 30 research articles, including scientific journals and conference proceedings, were reviewed. Research articles were selected based on the titles, keywords and abstracts. Fig. 1 represents the research process flow that has been followed for conducting this review article.

Fig. 1. Methodology followed for this study.

3. Basics of image processing based crack detection

Image processing is the way of controlling image properties to analyze and extract intended distinctive attributes from the images. Some set of rules or processes followed to extract the attributes from an image are known as image processing algorithms. Fig. 2 resembles the general implementation method of image processing.

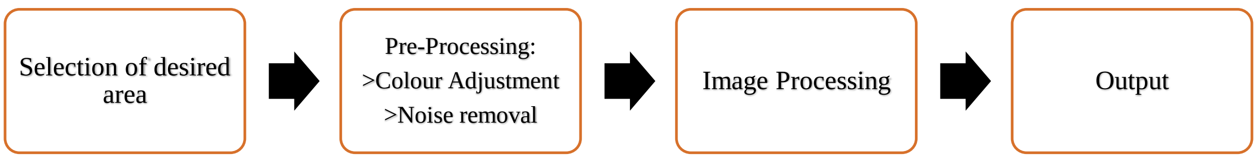

Fig. 2. General implementation stages of image processing.

An image-based crack detection system has several benefits, such as large storage of data and detection of the propagation of cracks on various engineering structure surfaces. During the initial days of implementing the image processing technique for identifying cracks, more emphasis was given to the features of objects and repeatability [8].

Crack detection and image processing techniques traditionally pursue predefined architectures that provide the observers with the desired crack detection and classification outputs.

In their review article published in 2017, Mohan and Poobal [9] proposed a famous architecture for image processing-based crack detection. They suggested that the detection process should begin with image collection in the architecture. In the next step, the collected images are preprocessed using gray scaling, smoothing, etc. The key processing algorithms are applied to the pre-processed images in the third stage. The cracks in the images are then detected using these processed images. Finally, different attributes such as crack width, length, and depth are extracted and evaluated in the architecture's final stage. The architecture proposed by them is given in Fig. 3.

Fig. 3. General structure of crack detection through image processing proposed by Mohan and Poobal [9].

In 2018, Vijayan and Geethalakshmi [10] proposed a quite similar but simplified architecture. The first phase in their proposed architecture is image collection or data set formation. After that, preprocessing methods such as smoothing and filtering are applied to the images in the database. In a single-stage, image processing and crack detection are combined. Processing algorithms, such as Otsu thresholding, statistical approaches, and thresholding techniques, are used here. Finally, CNN or Fuzzy-based algorithms are used to classify the detected images. The summarizations of the steps is given in Fig. 4.

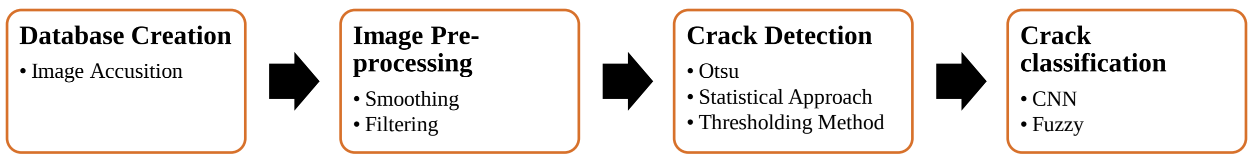

Fig. 4. Architecture of crack detection by image processing proposed by Vijayan et al. [10].

Liu et al. in 2019 [11], suggested a Full CNN based crack detection method using U-Net which is given in Fig. 5. Being, a deep neural network-based approach, for parameters tuning and hyper-parameters tuning the main dataset was divided into two parts, the training set and validation set. The 19 convolutional layered U-Net was trained with 57 input images from the training set. For the hyper-parameter tuning the rest of the images were used.

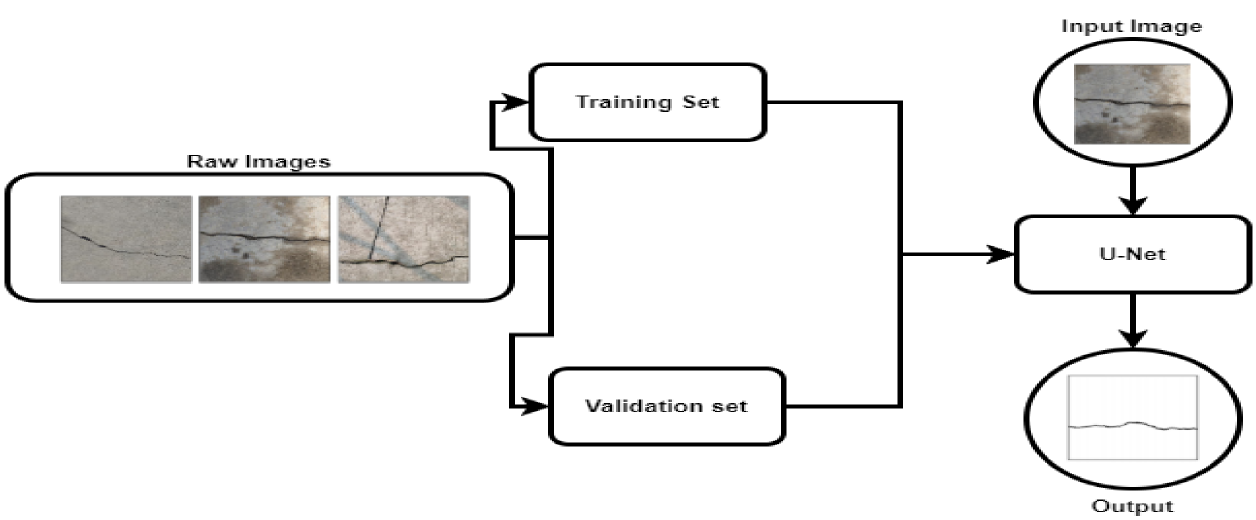

Fig. 5. CNN based crack detection using U-net [11].

The marked output images with defined cracks were received at the output layer after input images were inserted into the trained and tuned U-Net. Adam's optimizer and K-fold cross validation were used for optimization and validation. As a result, a more efficient algorithm was developed.

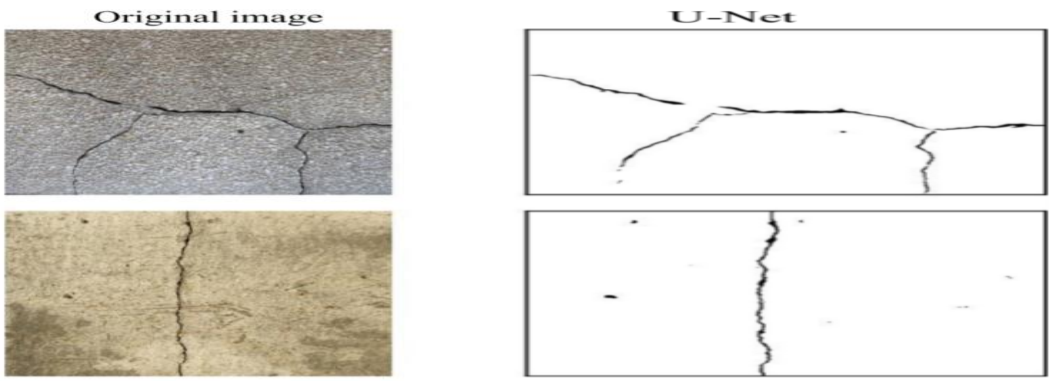

Fig. 6. Input original image (left) and U-Net image (right) [11].

Ren at al. (2019) [12], suggested a crack detection system for tunnels using an improved fully convolutional neural network. CrackSegNet was the name of the network. The neural network was built using a modular design that included encoder, decoder path, and 3X3 convolutions, followed by a 2X2 max pooling layer. The 409 images in the input dataset were augmented to create a new larger dataset of 919 images. This dataset was split into a training set and a validation set in a 4:1 ratio for training purposes. The initial RGB images were converted to grayscale and binary images before being used in the detection process. Finally, they were subjected to noise reduction before being inserted into the network. The crack segmentation algorithm returned the images with only cracks being marked in binary form (Fig. 7).

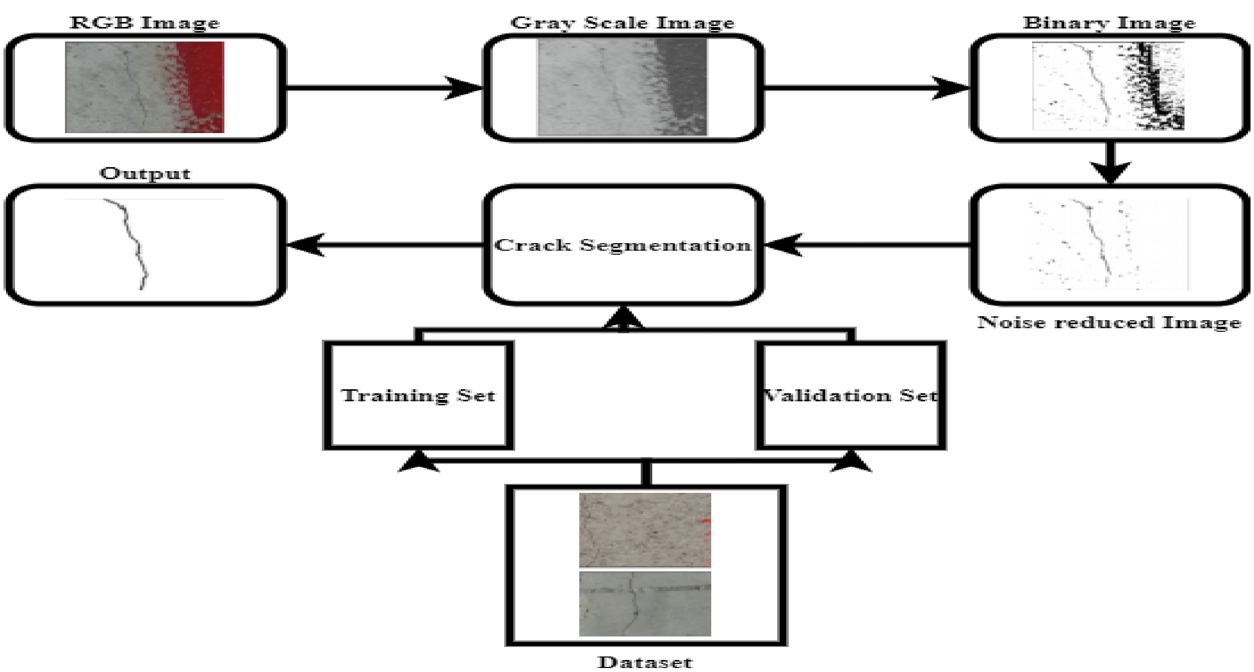

Fig. 7. Work flow of CrackSegNet network to detect cracks [12].

4. Analysis of publication activity dynamics

For this review article, leading peer reviewed journals and conference papers published in between 2015 to 2020, were surveyed and critically analyzed.

One of the very first papers on accurately evaluating and measuring values from concrete fractures was published in 2002. The experiment was carried out on concrete blocks [13]. Following that, multiple studies on crack detection using image processing were conducted. However, there has been a significant advancement in the algorithm and edge detection technique in the last six years. In recent years, proper edge detection and measurement of crack characteristics have been a significant concern. As a result, research papers were chosen based on the methodology and application of their research. Fig. 8 represents the publication frequency of the articles from 2015 to 2020, which has been analyzed in this review article.

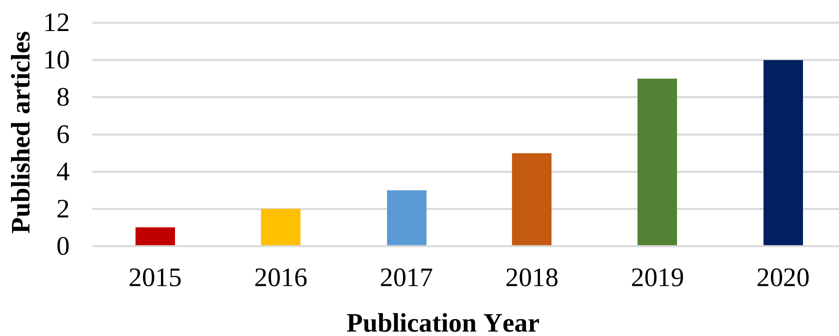

Fig. 8. Frequency of published articles on crack detection in between 2015 - 2020.

Word cloud represents the words which have been given more importance and have been used repeatedly by various research papers. It is a pictorial representation of the works of various researchers depending on their word usage in the titles. Fig. 9 represents the word cloud which has been generated using titles and keywords used by the authors from research articles published from 2015 to 2020. The larger the size of the words the more they have been repeated as keywords.

Fig. 9. Word cloud representing the keywords extracted from titles of reviewed articles.

From Fig. 9, it can be emphasized that most of the research work has been done on concrete structures and pavements where detection of the cracks were given more importance. Various segmentation and use of classifier can also be observed from the word cloud.

5. Literature review

In this review article, literature analysis has been divided into two sections. The first section provides a more comprehensive assessment of the available review articles on crack identification using various image processing algorithms. The second section is a comparison of several research articles that attempted to identify cracks and presented different image processing algorithms to do so.

5.1. Analysis of published review paper

Five major review articles were published in the last ten years dedicated to crack detection by image processing. The authors of these review papers examined through existing crack detection research studies that used various image processing algorithms. Machine learning and deep learning algorithms were included in some of the approaches. Based on the results of the reviews, the majority of the studies proposed a common architecture. The papers also included limitations and future scopes from the analysis. Table 1 summarizes the significant features and information provided by past review publications to better comprehend their significance in this study field and assist future researchers.

Table 1
Survey of published review article.

Sl. No.	Core Features	Ref.
1.	(a) Systematic analysis in order to highlight research problems. (b) 50 research articles were surveyed. (c) Key characteristics of each methods were determined. (d) Articles were classified depending on their type of image used. (e) Common architecture were suggested. (f) Processing methods, level of accuracy, level of error, as well as dataset-based performance were reviewed.	[9]
2.	(a) Common architecture was suggested (b) Analysis was done based on DL methods. (c) 15 research article were surveyed. (d) Finally they proposed that deep learning can be used to improve the identification of cracks in surfaces.	[10]
3.	(a) Focused on various crack detection techniques both old and new as well as their technological aspects. (b) Comparison was made between different methods. (c) Research was categorized based on algorithm type. (d) 24 literatures were surveyed.	[14]
4.	(a) Knowledge about cracking and its sourced were determined. (b) 112 papers were surveyed. (c) Existing and emerging, both types of methods were identified with their advantages and challenges. (d) Research articles were categorized based on direct and indirect sensing. (e) Model-based and model free data analysis were reviewed.	[15]
5.	(a) Various crack detection techniques, different methodologies adapted on concrete civil structures were reviewed. (b) A common architecture was suggested. (c) Different crack detection techniques were discussed. (d) The research articles were categorized based on algorithms. (e) Challenges and recommendation for future studies were given.	[16]

5.2. Review of published research articles

Review of the published research article has been done on a tabulated format. Articles were sub-divided based on their investigated crack surfaces. Six different tables has been constructed to represent those articles.

Table 2

Crack detection on traditional concrete structure surface.

Sl. No.	Image Type/ Sensor	Image processing Technique	Algorithms	Dataset	Key parameters/ Comments	Ref.
1.	Camera image	-	FCN (U-Net)	84 images	Precision = 0.90 Recall = 0.91 F1 = 0.90	[11]
2.	Camera image	-	FCN (VGG 16)	40,000 images	Max F1 (%) = 89.3 Average Precision (AP) (%) = 89.3	[17]
3.	Visual Sensor With laser beam	-	YOLO V3	1800 images. **Trained with**: Coco dataset	Accuracy = 94% Precision = 98%	[18]
4.	4K camera	Segmentation and Multiple Noise Reduction	Fuzzy Clustering	50 real concrete photographs.	Recall = 0.8 Precision = 0.9 Detects width of 0.3 mm or more.	[19]
5.	Camera image	Canny Edge Detection and width estimation	-	Images from the walls of K-Block, Nirma University	0.20 mm or less wide cracks went undetected.	[20]
6.	Smartphone camera		CNN (Efficient Net)	Dataset collected by Smartphone photos from a suspension bridge.	Accuracy = 0.9911 Precision = 0.9878 Recall = 0.9945 F1 Score = 0.9912 Accuracy (different dataset) = 0.9737	[21]
7.	Camera image	FAST, ORB, SIFT, SURF	-	-	Av. execution time, Fast = 461.9 ms ORB = 329.1 ms SIFT = 1476.5 ms SURF = 488.1 ms ORB and FAST were preferred	[22]
8.	Camera image	Otsu thresholding	CNN	Open source dataset with 20,000 cracked image	Accuracy = 98.25%, 97.18%, and 96.17% for the first, second, and third classifiers, respectively	[23]
9.	Camera Image	Semantic Segmentation	Mask R-CNN	100 & 150 images.	Accuracy = 0.9921 Sensitivity =0.7847 Specificity= 0.9933 Precision = 0.4044 F-measure= 0.4994	[24]
10	Camera Image	-	CNN	851 pictures from specimens after mechanical testing.	Accuracy = 92.27%	[25]
11	Camera image	-	Deep CNN (ConvNet)	More than 500 pavement pictures.	Precision = 0.8696 Recall = 0.9251 F1 = 0.8965	[26]
12	Camera Image	Adaptive Threshold Method	-	Two sets. First with 3 images & second with 200 concrete surface images.	TPR = 94.2%	[27]

Legend: FCN Fully Convolutional Network, CNN Convolutional Neural Network, R-CNN Region-based Convolutional Neural Network, FAST Feature from Accelerated Segment Test, ORB Oriented FAST and rotated BRIEF, SIFT scale-invariant feature transform, SURF Speeded Up Robust Features, TPR True Positive Rate.

Table 3
Crack detection on flexible pavement surface.

Sl. No.	Image Type/ Sensor	Image processing Technique	Algorithm	Dataset	Key parameters/ Comments	Ref.
1.	Sports camera	-	CNN (Dense Net 201)	Two datasets. CFD and EdmCrack with 1000 images.	Precision = 91.00% Recall = 93.22% F1 = 91.99%	[28]
2.	Camera image	Otsu thresholding	-	Collected RGB image	Calculated relative error = 3%	[29]
3.	Pave Vision 3D system	Ostu thresholding	-	50 Google images.	Specificity = 98.8% Precision = 77.27% Accuracy = 97.13% F-Score =76.09%	[30]
4.	Pave Vision 3D system	-	CrackNet-V	Images from last 5 years on different pavements. Image covers an area of 4 x 2 m^2	Precision = 84.3%, Recall = 90.12% F-1 = 87.12%	[31]
5.	Digital camera	-	CNN	2600 RGB images a distance of 80 to 100 cm.	Recall = 98.0%, Precision = 99.4% Accuracy = 99.2%	[32]
6.	Camera image	-	YOLO V3	From Highway Bureau. 3800 images for training sets and 400 for test sets.	Accuracy 88%	[33]
7.	Camera image	Unsupervised image processing	-	Two datasets. First 55 images from Google search engine (keyword "pavement cracks"). Second dataset is annotated road crack image dataset with 329 images.	Suitable as a pre-processing step and can provide rough estimation of damaged area in an image.	[34]
8.	Camera image	ROI and saliency map	-	Images from a highway.	Processing time = 20 fps Accuracy = 89.33%	[35]
9.	Camera Image	-	CNN	Collected Pavement images.	Pavement cracks were successfully calculated.	[36]
10.	CCD Array	Canny-HBT filter	-	Collected crack images.	PSNR = 11.15 (db) Entropy = 6.4054 Errors = 0.3699 FSIM = 0.6602	[37]
11.	RGB & Infrared Images	Retinex, Hessian-based method, Gabor filter, Otsu and Median filter	DBN	920 RGB and infrared images	Infrared + RGB, Precision = 0.92 F1 Score = 0.93 Recall = 0.91 RGB, Precision = 0.90 F1 Score = 0.88 Recall = 0.87	[38]

Legend: PSNR peak signal-to-noise ratio, FSIM feature similarity, ROI region-of-interest, DBN Deep Belief Network, RGB Red Green Blue.

Table 4
Crack detection on concrete tunnel surface.

Sl. No.	Image Type/ Sensor	Image processing Technique	Algorithm	Dataset	Key parameters/ Comments	Ref.
1.	Camera image	-	Deep FCN (CrackSegNet)	A total of 409 images from tunnel.	IoU = 38.2% Precision = 63.85% Recall = 47.46% F1 = 54.45%	[12]
2.	Robotic arm for capturing images	-	CNN & Fuzzy clustering	Images from Metsovo motorway tunnel in Greece.	Accuracy = 0.637 FNR = 0.280 FPR = 0.390 F1= 0.494	[39]
3.	Camera Image	CEM algorithm	-	Collected 1,000 pictures.	Accuracy = 91.4%	[40]

Legend: IoU Intersection over Union, FNR False Negative Rate, FPR False Positive Rate.

Table 5
Crack detection on concrete bridge surface.

Sl. No.	Image Type/ Sensor	Image processing Technique	Algorithm	Dataset	Key parameters/ Comments	Ref.
1.	CCD camera image	Otsu threshold segmentation and modified Sobel operator	-	Collected Gray Scale images.	Precision can reach 0.02 mm	[41]
2.	Camera image	-	YOLO v4-FPM	CFAR-10 & COCO	Recall = 0.978 F1 = 0.979 Precision = 0.00368	[42]
3.	CCD camera	Local adaptive Otsu and Sobel edge gradient detection	-	Images collected from bridges.	Algorithm is feasible in the real-time automatic detection of concrete bridge cracks.	[41]

Legend: CCD Charge-Coupled Device.

Table 6
Crack detection on rail tracks.

Sl. No.	Image Type/ Sensor	Image processing Technique	Algorithm	Dataset	Key parameters / Comments	Ref.
1.	Camera Image	Level Set Method	Fuzzy C Means	Images collected from railway tracks.	Entropy was 0.0016 for high resolution image and 0.020 was for level set method respectively.	[43]
2.	RAILSCOPE image acquisition system	Adaptive threshold method	-	From NRC Canada using a RAILSCOPE image acquisition system (IAS).	Computational speed increased	[44]

Table 7
Crack detection on steel structure surface.

Sl. No.	Image Type/ Sensor	Image processing Technique	Algorithm	Dataset	Key parameters / Comments	Ref.
1.	Multi-frequency EM scanner	-	Support Vector Machine	Scanned from stainless steel plates and carbon fiber-reinforced polymer (CFRP) plates	Detection rate = 89.7% Training time = 2.784 Testing time = 2.417	[45]

6. Analysis based on literature review

6.1. Analysis based on the level of accuracy

Based on the literature reviewed, accuracy level-based analysis was done to observe the performance of the approaches in proper detection of the cracks. Research articles reviewed have been categorized into four different types of grades based on their accuracy percentages: A (100-91%), B (90-81%), C (80-71%) and D (70-61%). From literature analysis, it was observed that on 32 research articles between 2015 - 2020, only eleven paper had justified their accuracy level, among which eight papers have achieved A-grade level accuracy. It can also be seen that out of the eight papers which have A-grade accuracy level, six articles had used CNN or CNN-based YOLO architecture for their crack detection model. However, the lowest accuracy level was observed for [28], which is about 64%. Accuracy level-based analysis result has been given in Table 8.

Table 8
Grading of reviewed literature based on accuracy level.

Grade	Research articles
A (100-91%)	[18,21,23–25,30,32,40]
B (90-81%)	[33,35]
C (80-71%)	-
D (70-61%)	[39]

6.2. Analysis based on algorithms

An algorithm based analysis was performed based on the results of the literature survey, and the outcome was used to form a pie chart in this section. Observing Fig.10, it can be seen that CNN (Convolutional Neural Network) algorithm has been used extensively for developing crack identification models. About 38% of literature has used CNN to develop their detection models, which is because of its low dependency on preprocessing and easier implementability. Fuzzy C-means Clustering, Deep FCN and YOLO V3/V4 algorithms were the subsequent most used algorithms with 14% usage among the papers, where YOLO is also a CNN based object detection algorithm. However, SVM, DBN, R-CNN and CrackNet-V were used at a low context of only 5%.

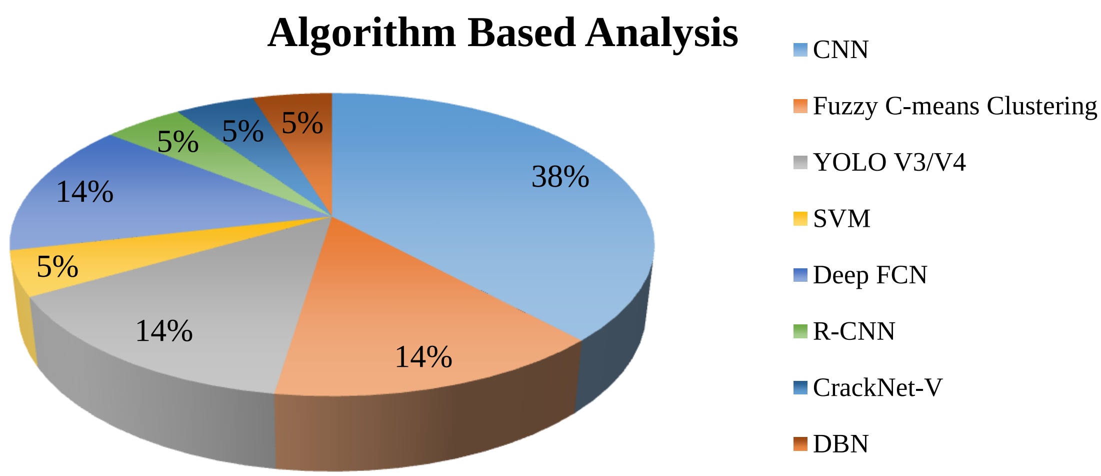

Fig. 10. Usage of different algorithms.

6.3. Analysis based on image processing techniques

From the research articles reviewed, the image processing approaches were extracted to form a bar chart in order to demonstrate the number of usage. The bar chart highlighted that Otsu thresholding for image segmentation was the most commonly used image processing approach in the research articles, with five articles employing it. While adaptive threshold, another image segmentation approach and the Sobel operator method were only utilized in two of the publications, other techniques such as Canny edge detection, CEM algorithm, Level set method, and others were only employed in a single paper.

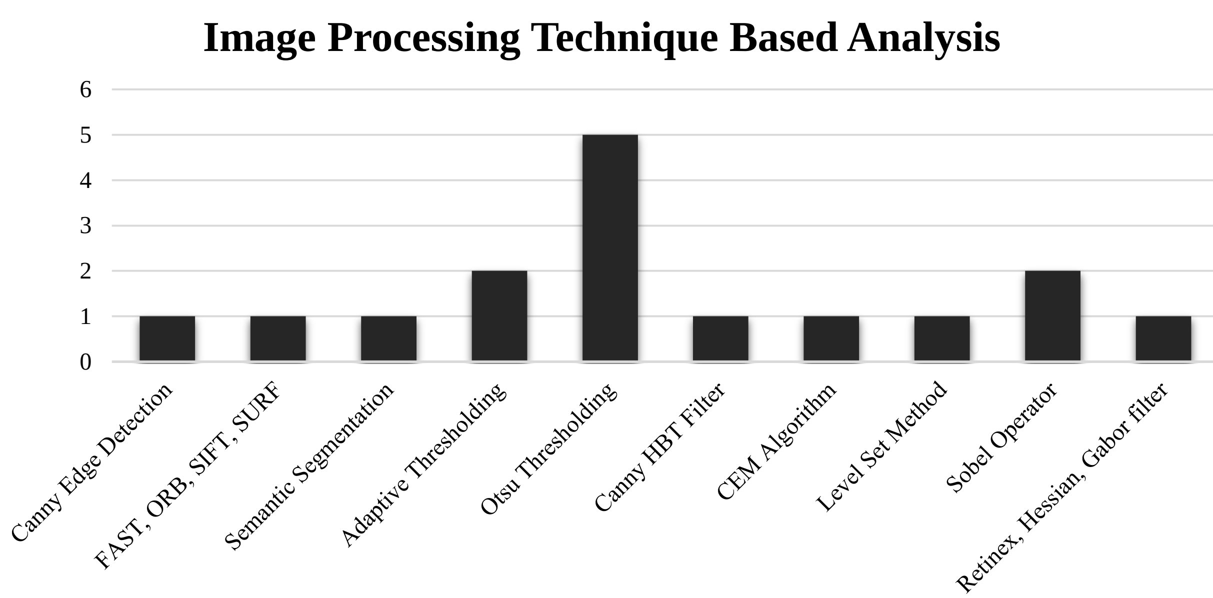

Fig. 11. Usage of different image processing techniques.

6.4. Factors affecting the accuracy of crack detection process

(I) Image Quality: Image quality plays a vital role for crack detection in a proper manner. If the image quality is not up to the mark then the noises in the surface can be detected as cracks. So, a minimum range of the pixels of image is to be is to be determined in order to carry out the work properly.
(II) Image Processing Technique: Selection of image processing technique and steps are important factor to process the image acquired accurately to carry out the further investigation. In this context, from literature analysis it was seen that Otsu thresholding, adaptive thresholding and semantic segmentation are better performing image processing techniques.
(III) Selection of Algorithm: Selection of algorithms play a vital role in the accuracy of the whole process, a suitable algorithm selection results into a better performing model with higher chances of detection. CNN and CNN based algorithms were seen to have a higher accuracy compared to other algorithms based on the literature analysis.
(IV) Number of Samples and Their Types: For the evaluation of the developed detection process, number of sample has been used and their wide range of variety plays a key role to assess the acceptability of the developed process.

7. Challenges and points to give more concern

1) Most of the research paper mainly focuses on the propagation of the cracks in the longitudinal direction. But, propagation in the transverse direction sometimes plays a crucial role, especially when the cracks' width needs to be determined. Therefore, longitudinal and transverse in both direction estimation of the propagation of the cracks should be done.

2) Estimation of the crack depth is very difficult to predict from sequence of images, especially for the cracks in open surfaces. So, a thermography based algorithm can be a better option to develop a process for the estimation of the crack depth.

3) Most of the research has been conducted by developing a system, focusing on a definite type of structure and cracks. So, an independent system which can quantify, locate and classify various types of different cracks by a common procedure will be more appropriate in order to use this method in practical analysis.

4) Resolution of the image plays a vital role for the accuracy and proper result. For camera-based analysis, there should be a minimum level of resolution below which the detection accuracy falls below the acceptable range.

8. Proposed approach

Image processing is the process of extracting key parameters from images in order to achieve a specific goal. An approach for image processing-based crack detection based on the information collected from reviewed research papers has been proposed in this survey study given in Fig. 12.

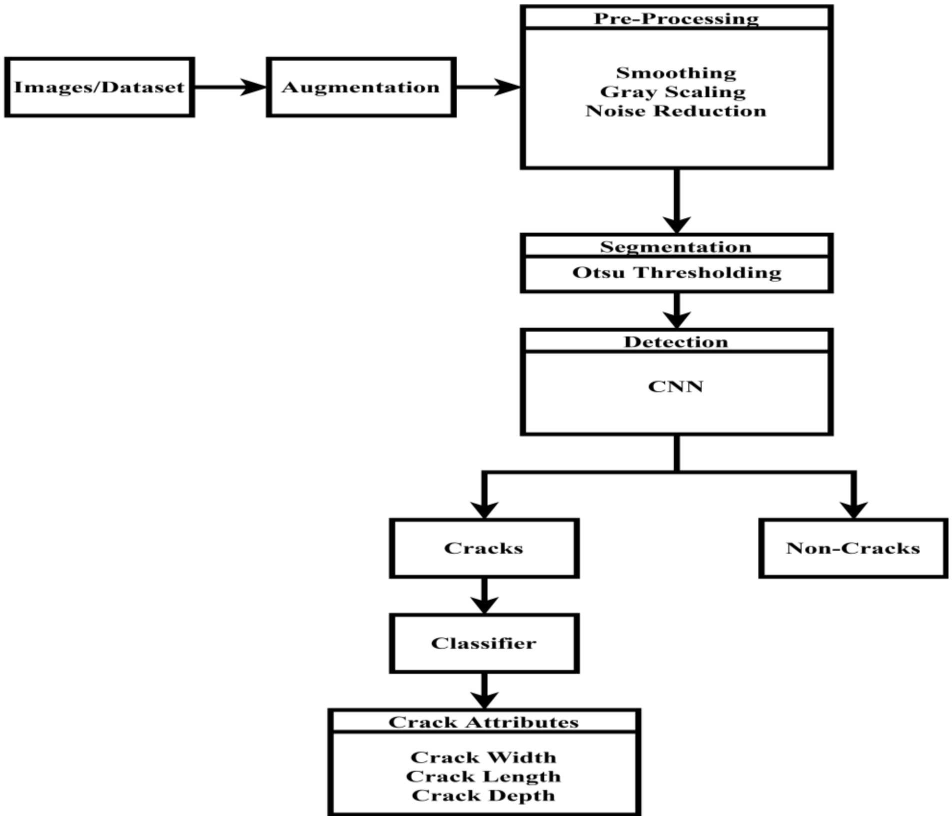

Fig. 12. Proposed approach for crack detection based on the results of the literature analyzed

The proposed approach is divided into 5 steps:
(1)Image collection/ dataset creation: The first step in the approach is to gather crack images and create a dataset.
(2)Pre-processing: The next step of the approach includes pre-processing of the images with smoothing, gray scaling, and noise reduction.
(3)Segmentation: This step includes segmentation of the images using Otsu thresholding for inserting into the detection process.
(4)Crack detection: In this stage, detection algorithm such as Convolutional Neural Networks can be used to detect either crack or non-crack images.
(5)Detection of crack attributes: The final step involves using classifiers again for the purpose of detection of crack length, width and depth.

9. Conclusion

Crack identification through image processing is a novel technique that reduces the time and cost to identify the cracks in the structure. In this review paper, a number of published articles depending on their experimental structure, steps followed, and outcomes, have been reviewed to make a summary and to justify the accuracy of image processing-based crack detection. After the literature review, based on the key information gathered from the survey, analysis was made to point out accuracy level, usage of the algorithm, and the key factors that affect this technique's accuracy. Based on the surveyed research articles, challenges and the critical points needed to give more concern have been figured out to help the researchers for developing a crack identification system that will be unique and accurate. It was observed that camera-based image processing has a great interest among the researchers due to its lower cost and multiple approaches. But the resolution of the images plays a vital role in this technique. The highest accuracy level was also observed in camera-based analysis, but steps for identification of the crack depth were missing in most of the papers. Moreover, the accuracy of the approaches to assess the developed method was not given in most of the research articles. Depending on the survey, a new image processing structure to detect cracks with all its parameters was proposed. The proposed structure was developed by synthesis of various approaches and based on their accuracy results. But, for developing a unique system, lots of practical implementations are needed. So, it can be concluded that image processing-based crack detection can be an excellent alternative to reduce the difficulties of human-based time-consuming approaches. But a general structure that will be fully applicable to any structure surface is needed.

In the future, we aim to develop a crack detection model based on the proposed approach given in this research study, which will detect the crack attributes with higher accuracy.

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