A Critical Review of Crack Detection Based on Image Processing

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Abstract – In order to extract meaningful observations from an image, it is essential to first convert it into a digital format and then apply a particular processing methodology. In the domain of image processing, it is a prevalent convention to consider all images as signals that are two-dimensional in nature, while utilizing conventional signal processing methodologies. The existence of surface fissures in concrete acts as an initial indication of probable structural deterioration. The utilization of image-based automated fracture identification is proposed as a viable alternative in situations where a human replacement is unavailable. This paper provides a critical review of crack detection using image processing. The scholarly literature encompasses a range of image processing techniques that can be employed for the automated identification of fractures and their respective depths. The present research involves a comprehensive examination with the objective of discerning the existing obstacles and past accomplishments within this area of investigation. A total of 24 publications related to the detection of Ato cracks have been selected for the purpose of conducting a comprehensive review. Following the review, a comprehensive analysis is performed on various image processing techniques, encompassing their respective objectives, degrees of accuracy and inaccuracy, as well as the datasets of images utilized. This study also presents future research efforts in identifying and resolving the problem of crack detection.

Keywords – Image Processing, Image Analysis, Image Compression, Crack Detection, Big Data Technology, Artificial Neural Network.

I. INTRODUCTION

The field of image processing technology is continuously advancing. Various industries, including agriculture, textile, and transportation, have successfully employed techniques such as image manipulation, coding, compression, and segmentation, among others. A nascent technical domain has surfaced, which concentrates on investigating image processing technology through the lens of big data technology. The objective is to construct an image processing model that can enhance the standard and efficacy of image processing. Conventional techniques for image processing are inadequate in managing the vast quantity of image samples that are presently accessible. The research conducted on big data has revealed that the image processing model that is based on it offers several advantages, including robust repeatability, high precision, extensive applicability, excellent adaptability, and significant potential for information compression. The stages of image processing are presented in **Table 1**.

Recently, novel methodologies have been proposed for the analysis of vast quantities of data. The development of image processing models that rely on big data analysis may encounter several technical challenges, including the computational demands in terms of time and memory, the intricacy of the algorithms required for feature extraction, recognition, and prediction analysis based on big data, and the necessity to present the outcomes of the analysis in a visual format. Furthermore, a significant concern pertains to the sluggish recognition speed of a given model. The increasing computational capacity has facilitated the utilization of big data in the realm of image processing, leading to its growing applicability. The development of image processing models utilizing big data analysis holds significant potential for implementation in various domains of image processing, owing to the scrutiny of fundamental principles, technologies, and advantages of big data technology in this field.

The initiation of cracks in engineering systems such as beams and concrete surfaces is mostly accredited to cyclic loading and fatigue stress at the microscopic level. The presence of cracks within a structure results in the occurrence of material discontinuities, which in turn leads to a reduction in the local stiffness. The implementation of preventive measures can be undertaken in advance of any potential harm or failure, provided that early detection of issues is achieved. Several processing techniques can be employed for the purpose of detecting cracks. There exist two distinct approaches to detecting a fracture. The testing process can be classified into two categories: destructive and nondestructive. The evaluation of surface defects is conducted through the utilization of both visual examination and surveying instrumentation. The presence of surface cracks on a structure can yield valuable insights into its age, extent of degradation, and structural integrity. These characteristics can be determined by analyzing the width, length, quantity and type of the cracks.

Table 1. Image Processing Phases	
Image Acquisition	In cases where the camera's output is not inherently digital, an analogue-to-digital converter is employed to convert the captured image into a digital format suitable for computer-based applications.
Image Enhancement	During this stage, the obtained image is subjected to manipulation procedures in order to satisfy the particular demands of the task for which the image is intended. The techniques in question are primarily intended to emphasize concealed or significant elements within an image, such as adjustments to contrast and brightness. The subjectivity of image enhancement is a notable characteristic.
Image Restoration	This particular stage pertains to enhancing the visual quality of an image and is deemed an objective process as the deterioration of an image can be ascribed to a mathematical or probabilistic framework. One potential application involves the removal of noise or blur from digital images.
Color Image Processing	The objective of this stage is to address the manipulation of images that contain color information, specifically those that are 16-bit RGB or RGBA in format. This may involve tasks such as implementing color correction or conducting color modeling within the images.
Wavelets and Multi-Resolution Processing	Wavelets serve as fundamental units for the representation of images at different levels of resolution. The process of subdividing images into smaller regions is commonly employed for both data compression and pyramidal representation purposes.
Image Compression	The compression of images is necessary for their transfer to other devices or due to limitations in computational storage capacity, thereby rendering it infeasible to retain the images at their original size. The significance of this aspect is also evident in the context of exhibiting images on the internet. For instance, on Google, a diminutive thumbnail of an image represents a considerably compressed rendition of the authentic image. The image is displayed in its original resolution solely upon clicking. This procedure conserves the utilization of network resources on the servers.
Morphological Processing	The extraction of image components that facilitate the representation and depiction of shape is imperative for subsequent processing or downstream tasks. Morphological Processing offers the necessary mechanisms, which are fundamentally mathematical procedures, to achieve this objective. Erosion and dilation operations are employed in image processing to enhance and soften the boundaries of objects, correspondingly.
Image Segmentation	The initial stage of this process entails the division of an image into distinct constituent segments, with the aim of facilitating the transformation and/or modification of the image's representation into a more significant and analytically tractable form. The process of image segmentation facilitates the allocation of computational resources towards the salient regions of an image, while disregarding the non-essential areas. This capability enhances the efficacy of automated systems.
Representation and Description	Typically, following image segmentation procedures, a crucial step involves determining whether the area that was segmented should be represented as a boundary or a complete region. The concept of description pertains to the identification of specific attributes that yield quantitative information of significance or serve as fundamental criteria for distinguishing between distinct categories of entities.
Object Detection and Recognition	Upon completion of the segmentation of objects from an image, as well as the description and representation phases, it becomes necessary for the automated system to assign a label to each object. This is done to inform human users of the detected object, such as identifying it as a "vehicle" or "person", among other possibilities.
Knowledge Base	The acquisition of knowledge can be facilitated by the identification of an object of interest within an image, which is accompanied by its corresponding object label and bounding box coordinates. The knowledge base can be utilized to encode any relevant information that may aid in resolving the issue at hand.

The development of automatic crack identification serves as a viable substitute for manual inspection methods that are both time-consuming and subjective, thereby enabling swift and precise analysis of surface defects. Consequently, a more robust methodology for conducting surveys has been implemented. The advantages of automatic fracture detection are significant in the context of non-destructive testing. The process of manual examination poses a challenge in achieving precise and unbiased assessment of deterioration. Automated crack identification can be facilitated through the utilization of non-destructive testing techniques, including but not limited to infrared and thermal testing, ultrasonic testing, laser testing, and radiographic testing. The utilization of imaging methodologies for the detection of fractures in non-invasive examination is increasingly becoming prevalent. The challenges associated with image-based detection are attributed to various factors such as the irregular form and size of cracks, inconsistent lighting and shade, concrete spall, and imperfections. Several detection approaches in image processing were proposed due to their straightforward implementation. These approaches could be widely categorized into four classes: practical technique, percolation-based method, morphological approach, and integrated algorithm.

This study aims to conduct a thorough literature review on the subject of crack detection, with the objective of assessing its present status and potential future developments. 24 publications were selected for analysis, with a specific focus on crack identification. The present survey is organized in a two-fold manner. Firstly, it presents a comprehensive framework for the identification of cracks in images through the use of image processing techniques. Secondly, it conducts a systematic review of the existing literature, categorizing the publications based on the type of images analyzed. The subsequent discourse presents a comprehensive examination that has been segmented into distinct components, namely the research objective, the dataset employed, the margin of error, and the level of precision.

The remaining part of the article is organized as follows: Section II provides a critical review of techniques of image processing, which include mechanical image processing techniques, IR-based image processing techniques, ultrasonic image based processing techniques, laser image based processing techniques, TOFD image based processing techniques, and other forms of image-based processing techniques. Section III provides a discussion of the results. In this section different analyses are provided: objective-oriented, dataset-oriented, accuracy level-oriented, image processing approaches, and IP-oriented crack detection for safety analysis. Section IV provides final remarks to the article as well as directions for future research.

II. CRITICAL REVIEW OF TECHNIQUES

In this study, we investigate various crack detection techniques that rely on image analysis, which are contingent upon the specific format of the image under consideration. This study encompasses a variety of image forms, including but not limited to camera images, ultrasonic images, infrared images, laser images, time of flight diffraction images, and other specialized forms.

Mechanical image processing techniques

This article presents a discussion on fundamental techniques of image processing, which can be implemented in cracks detection in mechanical structures. The assessment of the paper is contingent upon the visual representation captured by the camera.

From a mechanical perspective, surface cracks can be observed as displacement discontinuities. By utilizing DIC measurements and identifying a clear onset of deformation, it is possible to automatically detect the locations of cracks. Furthermore, the strains derived from the digital image correlation displacement field could be employed for fracture detection. The strain field available on the surface of the specimen is subject to a particular resolution and is consequently smoothed by filter masks. Resultantly, the development of displacement discontinuities at fractures leads to the occurrence of strain peaks, whose magnitudes are associated with the fracture kinematics. At present, the retrieval of fracture positions from DIC (Digital Image Correlation) data is limited to one-dimensional measurement lines.

Furthermore, automated identification systems for cracks rely on either longitudinal displacements or stresses to detect fractures. Nevertheless, the utilization of solely longitudinal data for detection purposes results in the production of solely individual fracture location data, with the absence of information pertaining to fractures that arise perpendicular to the measurement line. In addition, automating the process of tracing fracture courses by linking consecutive crack locations within user-defined searching areas for full crack patterns with branching fractures, poses a significant challenge. The limited practical utility of such methods is attributed to their directional bias and incapacity to manage fracture patterns that are more complex than the rudimentary ones.

The present methodology employed for fracture detection involves the utilization of two-dimensional image processing algorithms that depend on the magnitudes of primary tensile stresses to overcome these limitations and achieve crack detection that is not influenced by direction. **Fig 1** illustrates the utilization of morphological and thresholding thinning techniques to generate skeletons, which are subsequently employed to extract the fracture pattern from the primary tensile strain field obtained through digital image correlation (DIC). The latter aspect holds particular significance in accurately characterizing and tracing the phenomenon of crack branching. To identify the locations of cracks and uncracked zones, a threshold of 1 is applied to binarize the principal tensile strain field. This threshold value must surpass the summation of the highest elastic tensile material strains and the measurement noise level.

The resulting binary image distinguishes high strain areas with cracks from low strain areas without cracks. Consequently, the minimum width of a crack that can be detected is directly proportional to the user-defined value. To achieve well-defined fracture lines, the regions of high strain are reduced in thickness through the application of morphological techniques available in MATLAB's Image Processing Toolbox. Nevertheless, challenges emerge when dealing with wide cracks as the correlation may become locally lost in the vicinity of the cracks, which is depicted in **Fig 1** as the white regions in the principal tensile strain domains. Additionally, the resulting crack patterns may lack coherence across different measurement stages. In order to mitigate the initial issue, it is necessary to avoid direct detection via a measurement stage with correlation losses, as this method may result in the extraction of false positives and the failure to detect significant fractures of a larger size. Automatically attributing correlation losses to high stresses would be deemed inaccurate, as such losses may manifest in non-cracked regions as well. In instances where there is a development of cracks over time, as is often observed in tests with monotonic loading, a pragmatic approach has been adopted. This approach involves the detection of cracks through the utilization of previous measurement stages, achieved by merging the binarisaton of domains with a higher strain (as depicted in the combining phase in **Fig 1**). The second issue is resolved by depending on a solitary identification of the fissure pattern during a measuring phase that signifies the stabilized fissure pattern for application in all ensuing measurements.

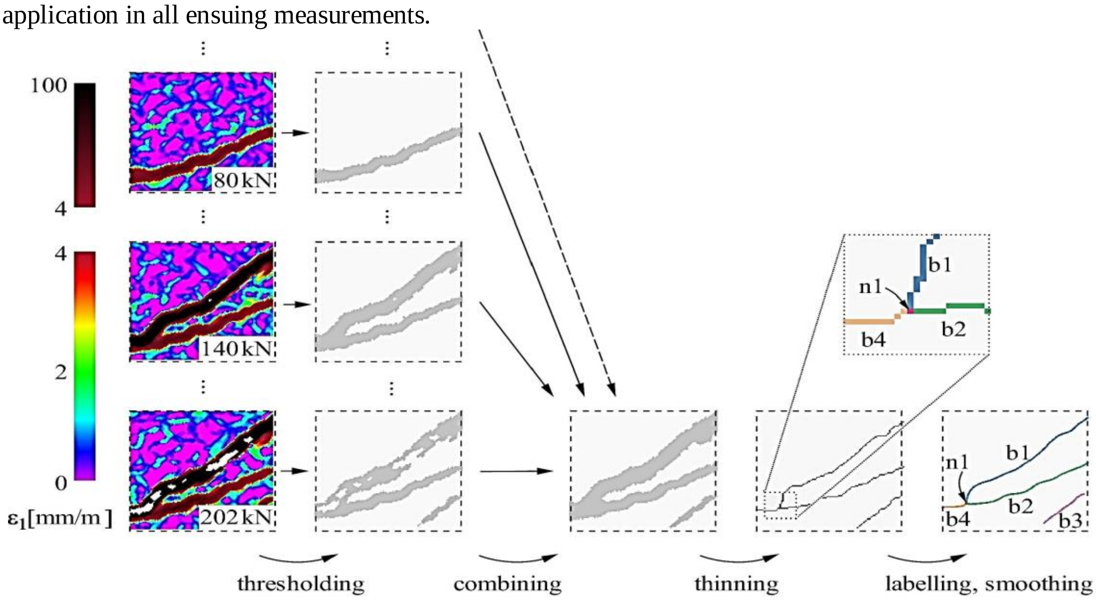

Fig 1. The crack identification technique involves a series of steps, including the application of thresholding to primary tensile strain fields obtained from multiple measurement stages, consolidation of regions with high strain, reduction of the consolidated regions to a fracture line skeleton through the use of morphological operations, smoothing and labeling of crack line branching, and ultimately, determination of the precise locations of cracks.

IR-based Image Processing Techniques

The present section employs infrared (IR) imagery to showcase the technique utilized for detecting cracks. Minkina [1] has proposed an Infrared (IR) thermography technique that involves Isotherm extraction and IR image rectification. This method enables the identification of cracks and facilitates the determination of their geometric orientation and properties that can aid in predicting the direction of crack propagation within the material. The assessment of diverse types of cracks, such as toe crack and longitudinal crack, can be expeditiously and effortlessly conducted through morphology analysis. The proposal employs the use of an IR camera analysis and subsequent image rectification to facilitate the geometric characterization of the faults. The identification of fractures was presented by Bao, Zhan, Wang, Zhu, Fan, and Li [2], which relied on the detection of notches within the irregularities. The method of rectifying IR thermography images has been employed to detect notches that are dependent on temperature.

Yang, Huang, Kong, and Liu [3] have introduced a method for identifying cracks that is contactless, non-invasive, and non-destructive. The thermal imaging device was employed to detect the infrared radiation emitted by the surface of the crack. The proposed methodology employs specular reflection for the purpose of fracture fault detection. Subsequently, the crack's position and morphology are ascertained by means of the reference surface. The results are analogous to those obtained through the acquisition of data in real-time at high velocities. Qiu, Pei, Yang, Liu, and Chen [4] developed a novel method for laser stimulated thermography utilizing a laser spot array source. In contrast to extant crack detection techniques that rely on infrared radiation, the proposed approach employs a Laser as its primary source of illumination. In this study, the utilization of contemporary laser stimulated thermography methods was employed to overlay images of local discontinuities, as opposed to the conventional approach of scanning a solitary laser point to visualize a fracture. The suggested approach incorporates the Finite Element Method (FEM) to effectively evaluate the implication of fracture geometry on thermal imaging. The recommended approach for crack analysis employing laser spot array thermography was predicated upon the thermal image gradient.

Furthermore, the incorporation of infrared (IR) imaging and the adaptation of the algorithm employed are additional instances of potential modifications that can be implemented within the crack detection procedure. Chen et al. [5] proposed a framework for processing infrared thermal images based on superpixels to detect fractures. The separation was generated through the utilization of fuzzy c-means clustering. Superpixels have been generated owing to their compatibility with crack borders. The superpixels were selected from both the unprocessed grayscale and the high-pass filtered iterations of the image.

Pracht and Świderski [6] have published a technique that utilizes ultrasonic IR thermography to identify fractures. Optically stimulated infrared thermography was employed for dependable fracture detection. The study employed principal component analysis (PCA) and pulse phase thermography, a wavelet transform-based technique that is reputed to exhibit greater noise immunity than Fourier magnitude, for the purpose of conducting analysis.

Iron, Martin, and van der Boom [7] have proposed a methodology that utilizes IR data obtained through an IR camera, along with geometric information extracted from a crack using a distinctive 3D macro-photogrammetric technique. The depth profiles were associated with diversified temperature figures across the segmented regions of the 3D geometric model. The provided methods have facilitated the establishment of a correlation between surface temperature data and depth. The proposed approach aims to develop a predictive model for estimating fracture depth in the context of thermographic inspection. The methodology involves utilizing a photogrammetric rectification algorithm on infrared images to establish a scale for the images. This enables the correlation between macro-photogrammetric depth data and thermal data in similar dimensions for every section. Additionally, a 3D framework of the crack is built to extract data depth across the different sections.

Ultrasonic Image Based Processing Techniques

This section presents a concise overview of the scholarly investigations conducted on the subject of fracture identification in mechanical structures through the utilization of ultrasonic image processing techniques. While phased array systems consisting of multiple transducers can be utilized in specific scenarios, single-point ultrasonic technologies that involve a single transducer are frequently employed for heavy metal components. In practice, there is a requirement for a non-destructive testing methodology that is expeditious, facile to operate, and generates a visual representation for the inspection of large-scale aluminum constituents on-site. This subset of ultrasonic infrared thermography is referred to by various names, including Vibrothermography, thermosonics, sonic infrared imaging, and acoustic infrared thermography. Occasionally, this technique could be employed for the purpose of identifying sealed cracks within dense aluminum plates.

The awareness of material vibration within the "near" ultrasonic frequency range (approximately 20 kHz and higher) has been prevalent for a considerable duration. The utilization of ultrasonic excitation and infrared thermographic imaging was initially documented by Villa-Gonzalez et al. [8]. The documentation successfully employed sweep frequency techniques to achieve resonant excitation of composites. This approach was utilized in their study. The technique of Ultrasonic IR thermography involves the application of single-frequency mechanical waves to the surface of a material to detect fractures and subsurface defects. This approach differs from the conventional thermal non-destructive testing (NDT) method, which relies on material surface's optical stimulation, Mechanical energy direct conversion into thermal energy by combination permits faults' selective imaging.

The application of infrared thermography is currently being employed in the examination of three distinct thermomechanical occurrences. These include: (1) the observation of mechanical stresses in materials through the evaluation of thermoplasticity and mechanical hysteresis, (2) the scrutiny of materials failure during fatigue (cyclic) loading, (3) the detection of cracks (structural defects) when subjected to ultrasonic stimulation. The present study is centered on the latter. The utilization of ultrasound for the purpose of initiating infrared thermography, also known as IR thermographic NDT, is regarded as a novel and inventive approach. Numerous research groups worldwide have conducted extensive studies in this particular area. The present investigation provides evidence that ultrasound IR thermography is a critical imaging approach, which can rapidly and effectively identify specific forms of engineering defects.

As previously observed, this approach can be utilized to identify fractures in ceramics and metals, along with disbonds and delaminations in composites. Ultrasonic IR thermography has significantly been employed in various contexts in recent times. These include, but are not restricted to, identifying internal delaminations in disbonds in airplane vertical stabilizers and graphite-fiber composites, non-destructive testing (NDT) of adhesive bond inspections, NDT of honeycomb sandwich panels, NDT of F16 airplane major landing glass and gears, and materials reinforced by metal fiber, and NDT of aircraft composite structures.

The effectiveness of ultrasonic IR thermography is affected by different factors such as material type, component design, vibrational modes, support conditions, excitation location, contact pressure, exciter-sample coupling, pulse length, and excitation frequency. Shi, Xu, Ma, Zhen, and Zhang [9] enhanced the testing parameters for detecting cracks in metallic high-pressured jet turbine disk utilized during the turbine's initial phase of operation. The experimental findings indicate that increased vibration amplitudes, trigger force, and ultrasonic pulse duration are positively correlated with improved fracture response. Khodaei, Biniaz Delijani, Hajipour, Karroubi, and Dehghan [10] conducted experiments on two metal samples which established a quantitative relationship between fracture length and vibrational stresses. The results indicated that temperature signals exhibit an increase with crack length. Further research is required to comprehensively comprehend the various factors that impact inspection outcomes in the examination of large aluminum structures that bear significant loads.

Laser Image Based Processing Technique

This section examines the potential application of Laser imaging within the image processing methodology for the purpose of identifying fractures in buildings. Zakeri, Nejad, and Fahimifar [11] proposed a method for detecting cracks that utilizes high spatial resolution imaging and laser scanning to measure 3D space, as documented in their publication. The proposed architectural design exhibits greater potential owing to the synergistic interplay between data collection and analysis. The successful detection and mapping of cracks were facilitated by three stages, namely shading correction, fracture identification, and crack mapping. The fracture has been meticulously mapped with a high degree of precision at the pixel level. Upon finalization of the definition, the fracture was remapped into the referenced coordinate system through the process of reverse engineering. The achievement was attained through the fusion of point clouds generated by a terrestrial laser scanner and corresponding images captured by a camera. Specifically, this was accomplished by converting the camera's coordinate system, which is based on pixels, to that of the scanner. Based on the available data, it can be inferred that the mean deviations between the total station and the terrestrial laser scan were 30, 16, and 14 millimeters in the x, y, and z axes, correspondingly.

Cao, Xiao, Wu, and Mao [12] devised a technique utilizing lasers to detect fractures in three dimensions. The sparse representation was devised as a means to disentangle the signal from the noise in a given profile. Following the characterization of the fissures, a hybrid lexicon was constructed. A mixed-function dictionary was constructed utilizing overcomplete exponential and trapezoidal membership functions. The researchers conducted a comparison of the sparse representations utilizing a corresponding pursuit technique. The utilization of wavelet and median filtering technique has validated the precision of the comparison. The researchers devised a primary profile simulation signal to evaluate the efficacy of their approach.

It is important to take into account the possible role of lasers in the process of distinguishing cracks. Authors in [13] have developed a novel methodology for quantifying cracks present on finished surfaces. The centroid approach has been utilized to perform mathematical calculations of fracture characteristics. A significant correlation was observed between the computed figures. The utilization of CCD technology and laser beam adaptation played a significant role in the positive outcome of their investigation.

TOFD Image Based Processing Techniques

This section pertains to the analysis of the Time of Flight Diffraction (TOFD) image for the purpose of detecting cracks. The TOFD approach relies on the utilization of cross-sectional imaging to leverage diffracted waveforms for non-destructive evaluation purposes.

Pissanetzky [14] have reported the use of sparse matrix replacement for the purpose of picture creation. The imaging technique employed by them entails the utilization of hyperbolas for the purpose of depicting the precise positions of fracture tips. The hyperbolic curves were generated through a stochastic process of manipulating the elements of a matrix with low density, utilizing the Hough transformation. The employment of split spectrum processing has led to an enhancement in the signal-to-noise ratio. The process of automating the detection of cracks involves analyzing the curve generated by the components of the sparse matrix.

Fatemi [15] have recommended an automatic interpretation approach for ultrasonic images using the TOFD approach, which is a nondestructive testing (NDT) approach. A mathematical morphological approach was employed to detect the discontinuities, followed by the extraction of the corresponding pixels. Subsequently, a technique for identifying patterns was employed to characterize the gaps. The target area was effectively utilized through the implementation of the watershed approach. The researchers utilized an erosion technique to eliminate the background of the image, thereby facilitating the identification of the image's associated characteristics. The method of skeletonization was adapted to selectively retain solely the curved configurations. The randomized Hough transform was employed to identify cracks in curved structures.

Other forms of Image-Centred Processing Techniques

Electroluminescence Image

Electroluminescence (EL) is a captivating optoelectronic concept. The EL camera records the luminous response of the specimen to the electric current that induces its electrocution. In contradistinction to the radiation emanating from a black body, this represents a wholly novel occurrence. The EL method is utilized for the purpose of visualization, akin to the utilization of high-resolution cameras. A method for detecting small cracks in the crystalline structure has been developed by [16] as reported in their study. The identification of micro fractures is a challenging task owing to the presence of various image irregularities such as dislocation clusters, grain boundaries, and gray level discontinuities. A filtering methodology predicated on anisotropic diffusion was devised by the authors. The implementation of the filtering technique resulted in an enhancement of the quality of the pixels. The mean precision of their discoveries is 90%.

UAV Camera Image

The secure execution of civil construction activities is contingent upon objectives such as the self-directed assessment of structural abnormalities facilitated by Unmanned Aerial Vehicles (UAVs). Nonetheless, the cost is not inexpensive. Automating the fracture detection procedure has the potential to yield substantial cost savings and enhance the frequency of inspection cycles. In recent times, there has been an increase in the availability of unmanned aerial vehicles (UAVs), which has led to the emergence of various novel applications, including transmission line inspections and refinery fractionation tower monitoring. The picture captured by a UAV camera exhibits distinct characteristics as compared to an image captured by a commercial camera, owing to its near-image quality and interdisciplinary nature.

The [17] propose the utilization of an Unmanned Aerial Vehicle (UAV) and multiple image processing algorithms for independent evaluation of building defects in fracture identification within building structures. Unmanned aerial vehicles (UAVs) ought to be outfitted with an integrated computer system that can facilitate the execution of said algorithms. Two image processing-based techniques have been employed for the purpose of crack detection. The Sobel operator, also known as the Sobel filter, is utilized as a means of detecting edges in their initial methodology. The Sober filter is a notable feature in the field of discrete differentiation. The output of a Sobel manager was either the magnitude of the gradient vector or the gradient vector at every pixel. The Particle Filter that is a non-parametric filter reliant of the Bayes approach was ranked as their second most preferred choice. The particle filter algorithm endeavors to establish a correlation between the intensity of pixels and the quantity of adjacent pixels, with the aim of predicting the presence or absence of a crack in a given segment of an image.

SEM Image

Scanning electron microscopy (SEM) and optical microscopy (OM) are widely utilized microscopy techniques. The latter option is considered to be the conventional approach and has been utilized for a minimum of two centuries, albeit in the form of a relatively rudimentary device. This methodology is alternatively referred to as optical microscopy. Several distinguishing features differentiate OM from SEM, including the following characteristics: (a) In contrast to scanning electron microscopy (SEM), which primarily operates on the basis of electron emission, optical microscopy (OM) relies on the use of light. Basic optical microscopy is characterized by the use of a single lens, while compound optical microscopy employs two lenses. The magnification of images in lenses is achieved through the phenomenon of light refraction. In contrast to optical microscopes, which have a limited magnification range of 400-1000 times, scanning electron microscopes are capable of magnifying up to 300,000 times their original size. The utilization of OM enables the examination of substances in both liquid and solid states.

However, it is feasible to discern a limited number of substantial fragments and a negligible amount of organic matter. The reason for this is that OM is limited to processing small samples with a specific thickness. Nevertheless, SEM provides a more comprehensive examination of the subject matter through the utilization of grayscale images. It can be inferred that the utilization of structural equation modeling (SEM) incurs higher expenses compared to ordinary least squares regression (OM) and presents challenges in terms of upkeep. The OM images precisely depict the authentic color tones of the subject matter being examined. **Fig 2** depicts the utilization of compound lenses in optical microscopy. There are three types of optical microscopes that are commercially available to consumers, namely the petrographic microscope, the automated optical microscope, and the stereo zoom optical microscope. The employment of SEM (scanning electron microscopy) analysis or methodology is prevalent in research. The technique in question is deemed dependable for investigating substances within the sub-nanometer to micrometer range. The utilization of the scanning electron microscope (SEM) enables the acquisition of highly intricate images of a diverse range of materials, with the potential to magnify up to one million times.

Fig 2. Optical Microscopy with Compound Lenses

Fig 3: SEM Quanta Device

The integration of Energy Dispersive X-ray Spectroscopy (EDS) and SEM provides both qualitative and semi-quantitative data. The integration of both techniques possesses the capability to unveil novel information regarding the material constitution of scanned specimens, which cannot be obtained through traditional laboratory examination. The study employs a SEM Quanta instrument for materials science, which is highly refined, as depicted in **Fig 3**. The apparatus is equipped with a pressure mechanism that can be modified to suit a diverse range of samples, including those that require minimal or no prior preparation. The equipment is capable of analyzing samples with a maximum diameter of 200 mm and height of 80 mm. The device exhibits a maximum magnification capability of 300,000x. The utilization of SEM is applicable to a diverse range of materials, encompassing both organic compounds and inorganic solids such as metals and polymers.

The [18] developed a fracture detection technique utilizing SEM images. The SEM images underwent a process of nodule removal and background cleanup, followed by histogram-based threshold binarization. The objective of their endeavor was to convert scanning electron microscope (SEM) images into binary format in order to enhance the differentiation between fractures and the adjacent background. Their study employs a methodology to measure the spatially fragmented region by utilizing the histogram’s second derivative retrieved from the Prewitt vertical edge detector and the Laplacian of Gaussian (LoG). Prior to conducting a comparison of scanning electron microscope (SEM) images, the normalization of contrast was performed by means of adjusting the intensity values for each respective image. The quantification of fractures was performed by calculating the pixels that had undergone segregation through different techniques of crack enhancement and segmentation.

Probe Image

The microscope probe represents a microscope that utilizes high-resolution color imaging. The probe's image spatial resolution ranges from 3 micrometers per pixel to an indeterminate value. Flexible probe imaging and context imaging techniques are utilized to facilitate robotic field research. In [19] proposed a load differential methodology. The evaluation of crack detection was conducted through the measurement of load-dependent variations in crack apertures. The guided wave signals were subjected to a comparative analysis with data that was free from damage. Consequently, the load differential approach underwent modifications. A limited number of piezoelectric transducers were employed to demonstrate this phenomenon on a specimen made of aluminum plate. The application of tensile stresses resulted in the opening of fractures, as observed through the utilization of the delay-and-sum imaging methodology.

Sensor Image

The sensor is capable of detecting pertinent conditions and subsequently transmitting the acquired data. An imaging sensor is a device that is capable of detecting and transmitting the data necessary to form an image. Through the conversion of waves into signals, it is possible to retrieve information in the form of transient electrical impulses. The waves in question may encompass a range of electromagnetic energy, extending beyond the visible spectrum of light. In [20], authors proposed a method that integrates magnetic flux leakage, thermography testing, and eddy current to increase the identification of near-surface faults in conductive and magnetisable specimens. Various signal processing methods were proposed to standardize the data, enabling the fusion of pixel-level data. Both pixel-by-pixel and multi-scaled fusion of data techniques have been employed. Brokaw [21] has recommended approaches for signal normalization to enable the integration of signal-level observations obtained from distinct non-destructive testing (NDT) imaging experiments. Following the normalization of the signals, the researchers integrated the data through the utilization of fundamental algebraic fusion methodologies.

Radar Image

The radar image can be likened to the image obtained through the use of a flash camera, wherein the ground is illuminated with light to capture an image, with the exception that radar functions at radio wavelengths instead of visible wavelengths. Data is captured by the radar through the utilization of an antenna and digital computer tapes. Imaging radar technology can be utilized to produce two-dimensional images. Radar images consist of a multitude of small dots. The radar backscatter emanating from the ground is observed in the form of discrete pixels. Regions exhibiting high levels of brightness are indicative of intense backscattering, while those characterized by low levels of darkness suggest minimal scattering. Wu et al. [22] have developed a 60 GHz V-band imaging radar model for non-invasive fracture detection of packed ceramic tiles based on the millimeter wave technology. The principal objective was to detect fissures while minimizing the occurrence of erroneous positive identifications. This study employed an adaptive approach utilizing statistical analysis to achieve its objectives. The development of a crack detection technique involved the utilization of mathematical modeling and optimization through a multi-objective generic algorithm.

Microwave Image

Microwave imaging is an advanced iteration of conventional radar techniques. The process of detecting hidden or embedded objects within a structure or medium involves the utilization of electromagnetic waves within the microwave frequency range, specifically ranging from 300 MHz to 300 GHz. The classifications of these entities could potentially fall under the categories of either quantitative or qualitative. The process of determining parameters through the resolution of a nonlinear inverse problem is commonly referred to as inverse scattering. Li et al. [23] propose a microwave imaging framework as a superior alternative to existing non-destructive evaluation and testing methods (NDE/NDT). The related sensors can be utilized in a non-contact manner. Cutting-edge 3-D imaging technology has been utilized to detect fissures in anisotropic materials. The retrieval of equivalent currents corresponding to a sparse fracture profile is accomplished through the utilization of 3D MOM (Method of Moments) matrices and a compressive sensing solution that is founded on Bayesian principles.

Video Image

This article pertains to the technique employed for the manipulation of video images. This criterion involves the processing of data segments extracted from videos in order to identify any interruptions. Thomson-Jones [24] developed an evaluation of the performance of digital image technology for detecting cracks on reinforced concrete bridges. Grayscale images, frame rates, noise filters, and edge detection have all been subject to scrutiny. The Harris and SV methodologies were employed for the purpose of detecting edges. A crack-detection software has been developed utilizing Visual C++6.0. Upon examination of 15 distinct video images of bridges, it was determined that the degree of imprecision was below 10% for fissures measuring between 0.2 to 0.3 mm in width, and below 6% for crevices measuring 0.3 mm or greater in width.

III. RESULTS AND DISCUSSION

This part of the article presents the findings of our research on crack detection, which was informed by a comprehensive review of the relevant literature. Our study considered various factors, such as accuracy analysis, objective analysis, error analysis, and image processing method analysis.

Objective-Oriented Analysis

In this discourse, we examine the analysis of fracture detection criterion based on objectives, utilizing the bar chart depicted in **Fig 4**. The objective of identifying cracks may differ significantly depending on the characteristic that facilitates such identification. This investigation utilizes measurements pertaining to the length, surface, direction, breadth, depth, and location of the crack's propagation. The estimation of fracture volume is a concerning factor in various plans due to the surface detection of the fracture. Out of the 24 papers examined, only 12 were able to attain the desired crack-free surface. The objective of crack length was attained in the investigations conducted the rest of the papers. The objectives of breadth and length are both reported. The width of the crack was subsequently assessed in six of the publications under consideration. The analysis of the literature leads to the conclusion that the majority of techniques primarily centered on the examination of fracture surfaces.

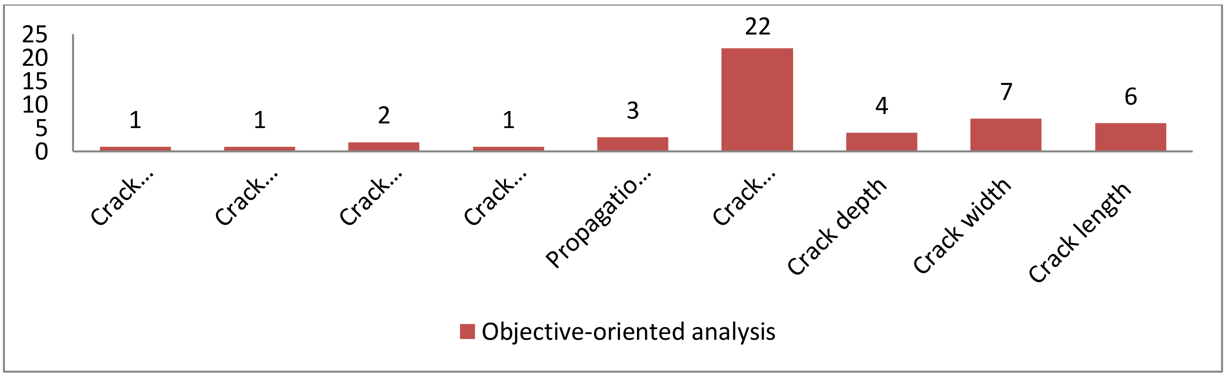

Fig 4. Chart Representing the Objectives

Dataset-Oriented Analysis

This part of the article entails an examination of the datasets employed by the structures being investigated, as depicted in **Fig 5**. The analyses presented in this study were generated using datasets sourced from multiple institutions and organizations, such as Real, TAMU, BYTEC, USNF, GRAI, POSCO, LAWP, SURFCOAT, CRST, TITS, NSFC, among others. Many scholars have placed their reliance on empirical data derived from their respective experiments. The datasets were compiled utilizing photographs that were available within the local vicinity. Several studies utilized data obtained from various sources such as LAWP, CNRS, TAMU and TITS. In summary, it can be observed that a significant proportion of scholarly articles have utilized authentic datasets to facilitate their crack detection endeavors.

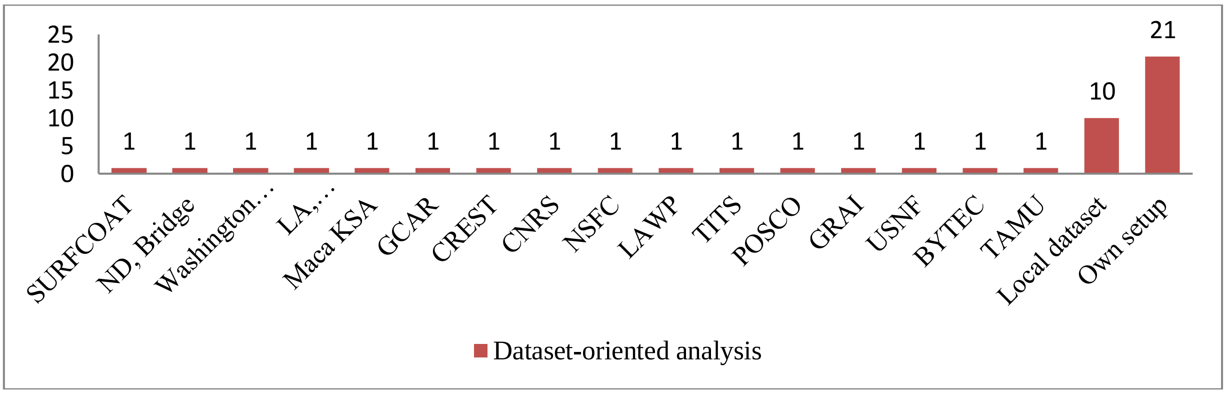

Fig 5. A chart of the Dataset-Oriented Analysis

Accuracy Level-Oriented Analysis

The evaluated articles are categorized into six groups based on their respective scores, which are as follows: below 70%, 75%, 80%, 90%, 95%, and over 95%. The literature reports accuracy rates exceeding 90% in this particular case. The references used exhibited accuracies ranging from 90% to 95%.

Error Level-Oriented Analysis

The present analysis displays the margin of error by means of the extent of the fracture that remained undetected. Inaccurate mapping results can lead to an increase in error level when the extracted data from a crack does not align with the corresponding comparison values. We adhere to the error range of 0.1-0.3%. As per the findings of this article, the highest potential deviation recorded was 1.20.

Image Processing Approaches-Oriented Analysis

Various methodologies were utilized in the study, including a morphological approach. Morphological techniques refer to a collection of non-linear operations that are implemented on an image, taking into account its shape or distinctive features. These operations include watershed transform, closure, opening, top-hat filtering, dilation, and erosion. The utilization of wavelet transform has been implemented by certain systems due to its heightened efficacy as a processing methodology. The wavelet transform is rated as a fundamental approach for time-frequency transformation. It bears similarities to Fourier transform, although composed of a different merit function.

The numerical values exhibited a range spanning from 11 to 23, 38, and 46. The utilization of the Correlation methodology, which entails the amalgamation of images through the implementation of DIC techniques, has been implemented in various proposals. The Digital Image Correlation (DIC) method can ascertain the three-dimensional shape and displacements of a loaded object through the utilization of gray value digital images. The Randomized Hough transform was employed as a viable alternative to the analysis based on reduced images. The Randomized Hough transformations are considered to be crucial techniques for object identification in numerous computer vision models. The Randomized Hough transform refer to a probabilistic adaptation of the conventional Hough transform that is commonly employed for detecting curves. In the pre-processing stage, segmentation was facilitated through the utilization of various techniques such as the threshold approach, Otsu's method, and the superpixel algorithm. The process of clustering-based picture thresholding is executed in an automated manner by utilizing Otsu's technique.

The statistical methodology is applied consistently throughout the entire process of data acquisition, analysis, interpretation, presentation, and arrangement. The utilization of texture analysis constituted a pivotal element in certain instances of the detection process. The utilization of data fusion filtering has been employed to augment the precision of the current evaluation of the state factor of a particular model. The process of skeletonization is employed to derive a shape component that is region-based and characterizes the global structure of an object. The extraction of second order arithmetical texture features for motion approximation involves the use of the GLCM. Photogrammetry is the discipline that involves the acquisition of measurements from images, with a particular focus on accurately determining the positions of surface points. This field encompasses both artistic and scientific aspects. Photoacoustic imaging, a modality used for biological imaging, is founded on the principle of the light acoustic effect. The utilization of laser pulses in photoacoustic imaging is advantageous as it does not result in ionization of the imaged tissue. The study indicates that the post-processing stage is where the most notable enhancements in image processing were executed.

IP-Oriented Crack Detection for Safety Analysis

The identification of cracks in civil buildings through automated means has been a challenging problem that has been the subject of research for several decades, owing to the intricate nature of such structures. The presence of surface cracks can serve as an initial indication of the deterioration of a building. Early detection and regular maintenance are crucial in preventing extensive damage caused by the spread of cracks. The process of manual inspection is dependent on the proficiency of the inspector and is limited to locations that are readily reachable. In comparison to human-based inspection techniques for real-time crack identification, the utilization of image-based algorithms for autonomous detection of cracks may offer several advantages, including the reduction of human errors, decreased time requirements, and enhanced cost-effectiveness. Multiple techniques are available for crack detection, and the utilization of mobile cameras enables the acquisition of images from areas that are typically out of reach.

The significance of safety has gained prominence in various industries, leading to an increasing corpus of research aimed at enhancing crack detection mechanisms. The utilization of image processing has become a prevalent method for detecting fractures due to its high level of dependability. Fracture detection is vital for monitoring subway tunnel safety, which involves the monitoring of subway tunnels through the utilization of image processing techniques. Furthermore, engineers employ image-based reconstruction techniques to facilitate automated fracture identification and digital crack measurements. The identification of cracks on pavement has been incorporated with the aim of achieving accurate and effective detection. In this, an algorithm is employed to process images of pavement cracks with the aim of eliminating isolated noise points, smoothing out edges, and enhancing the accuracy of segmentation. Furthermore, the utilization of morphological expansion corrosion has been employed for the secure acquisition of fracture data.

IV. CONCLUSIONS AND FUTURE RESEARCH

The process of crack examination involves two sequential steps, namely detection and measurement. The relevance of this approach within the field of civil engineering is attributed to its association with the dependability, durability, and adaptability of concrete structures. Several automated methods for crack inspection have been proposed utilizing image processing, artificial neural network, and machine learning algorithms. The crack inspections exhibited superior performance compared to the conventional human-based approach, which relies on the inspectors' subjectivity, owing to their efficiency and objectivity. The fracture detection task exhibited notable performance by techniques based on artificial neural networks. However, the practice of crack measurement has rarely considered such techniques. The present study proposed an innovative framework for the purpose of conducting a thorough and effective inspection of cracks in concrete ground structures. The utilization of artificial neural networks within the framework involves the identification of fractures through a two-step process. Firstly, the cracks present within the input image are segmented, and subsequently, the resulting patches are classified. Secondly, image processing techniques are employed to assess the characteristics of cracks, such as their dimensions in terms of length and width. The empirical evidence substantiated the proposed theoretical framework's capacity to yield fracture properties consistently over multiple iterations.

The present study provides a thorough examination of the diverse image processing approaches currently employed for the identification of fractures in artificial structures. The principal purpose of this article was to scrutinize and assess the currently available fracture detection systems that rely on image processing. The present investigation involved the analysis of 24 scholarly articles with a specific focus on the detection of cracks. Our review has been concluded on the basis of the assessment of these five attributes. The initial approach involves an objective-oriented evaluation that considers various parameters such as the extent of crack width, crack length and the fracture propagation direction. The study also examined the datasets utilized by these methodologies and observed that a significant proportion of them employ actual data to enhance efficiency and convenience. Subsequently, the analyses are examined with respect to their accuracy and, in specific circumstances, their inaccuracy. The study on the image processing mechanisms of each system has been concluded. Furthermore, we delineate various unresolved inquiries that could prove advantageous to scholars in the domain of crack detection systems based on image processing in subsequent studies. The study has led us to infer that researchers who conducted comprehensive damage analysis tended to utilize camera-type images and sophisticated segmentation algorithms, such as threshold techniques and re-structural feature extraction methods. This study provides a comprehensive investigation of noninvasive techniques for detecting cracks. In the future, we aim to conduct a review of the various approaches utilized for fracture detection based on intrusive methods.

Data Availability

No data was used to support this study.

Conflicts of Interests

The author(s) declare(s) that they have no conflicts of interest.

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Ethics Approval and Consent to Participate

The research has consent for Ethical Approval and Consent to participate.

Competing Interests

There are no competing interests.

References

[1]. W. Minkina, "Theoretical basics of radiant heat transfer – practical examples of calculation for the infrared (IR) used in infrared thermography measurements," Quant. Infrared Thermogr. J., vol. 18, no. 4, pp. 269–282, 2021.

[2]. X.-L. Bao, X. Zhan, L. Wang, Q. Zhu, B. Fan, and G.-Y. Li, "Automatic identification and segmentation of orbital blowout fractures based on artificial intelligence," Transl. Vis. Sci. Technol., vol. 12, no. 4, p. 7, 2023.

[3]. L. Yang, H. Huang, S. Kong, and Y. Liu, "A deep segmentation network for crack detection with progressive and hierarchical context fusion," J. Build. Eng., vol. 75, no. 106886, p. 106886, 2023.

[4]. J. Qiu, C. Pei, Y. Yang, H. Liu, and Z. Chen, "Laser array spots thermography for detection of cracks in curved structures," Int. J. Appl. Electromagn. Mech., vol. 64, no. 1–4, pp. 385–391, 2020.

[5]. X. Chen et al., "Impacts of inter-annual cropland changes on land surface temperature based on multi-temporal thermal infrared images," Infrared Phys. Technol., vol. 122, no. 104081, p. 104081, 2022.

[6]. M. Pracht and W. Świderski, "Experimental testing of aramid composite applied in ballistic armour by ultrasonic IR thermography," Probl. Mechatron. Armament Aviat. Saf. Eng., vol. 10, no. 2, pp. 79–88, 2019.

[7]. M. A. Iron, J. M. L. Martin, and M. E. van der Boom, "Mechanistic aspects of acetone addition to metalloaromatic complexes of iridium: a DFT investigationElectronic supplementary information (ESI) available: selected geometric data, calculated structures of all complexes and full computational details. See http://www.rsc.org/suppdata/cc/b2/b210622a/," Chem. Commun. (Camb.), no. 1, pp. 132–133, 2003.

[8]. J. M. Villa-Gonzalez et al., "A simple strategy for improving infrared thermographic imaging with smartphone accessories in dermatology," Clin. Exp. Dermatol., 2023.

[9]. Z. Shi, X. Xu, J. Ma, D. Zhen, and H. Zhang, "Quantitative detection of cracks in steel using eddy current pulsed thermography," Sensors (Basel), vol. 18, no. 4, p. 1070, 2018.
[10]. M. Khodaei, E. Biniaz Delijani, M. Hajipour, K. Karroubi, and A. N. Dehghan, "Analyzing the correlation between stochastic fracture networks geometrical properties and stress variability: a rock and fracture parameters study," J. Pet. Explor. Prod. Technol., vol. 11, no. 2, pp. 685–702, 2021.
[11]. H. Zakeri, F. M. Nejad, and A. Fahimifar, "Image based techniques for crack detection, classification and quantification in asphalt pavement: A review," Arch. Comput. Methods Eng., vol. 24, no. 4, pp. 935–977, 2017.
[12]. T. Cao, A. Xiao, L. Wu, and L. Mao, "Automatic fracture detection based on Terrestrial Laser Scanning Data: A new method and case study," Computers & Geosciences, vol. 106, pp. 209–216, 2017. doi:10.1016/j.cageo.2017.04.003
[13]. "Hair cracks, crazing or map cracks on concrete surfaces," ACI Journal Proceedings, vol. 2, no. 1, 1906. doi:10.14359/16406
[14]. S. Pissanetzky, "Sparse matrix algebra," Sparse Matrix Technology, pp. 233–270, 1984. doi:10.1016/b978-0-12-557580-5.50012-0
[15]. M. Fatemi, "Digital processing for improved ultrasonic abdominal images," Ultrasonic Imaging, vol. 2, no. 2, p. 177, 1980. doi:10.1016/0161-7346(80)90158-3
[16]. K. Ashok, M. Ashraf, J. Thimmia Raja, M. Z. Hussain, D. K. Singh, and A. Haldorai, "Collaborative analysis of audio-visual speech synthesis with sensor measurements for regulating human–robot interaction," International Journal of System Assurance Engineering and Management, Aug. 2022, doi: 10.1007/s13198-022-01709-y.
[17]. H and A. R, "Artificial Intelligence and Machine Learning for Enterprise Management," 2019 International Conference on Smart Systems and Inventive Technology (ICSSIT), Nov. 2019, doi: 10.1109/icssit46314.2019.8987964.
[18]. Haldorai, A. Ramu, and S. Murugan, "Computing and Communication Systems in Urban Development," Urban Computing, 2019, doi: 10.1007/978-3-030-26013-2.
[19]. Haldorai and U. Kandaswamy, "Energy Efficient Network Selection for Cognitive Spectrum Handovers," EAI/Springer Innovations in Communication and Computing, pp. 41–64, 2019, doi: 10.1007/978-3-030-15416-5_3.
[20]. A. P. Brokaw, "Sensor Signal Normalization," Analog Circuit Design, pp. 97–116, 1994. doi:10.1007/978-1-4757-2310-6_7.
[21]. X. Wu, R. Li, and P. Zhang, "Radar fusion imaging based on attributed Scattering Center model," 2021 CIE International Conference on Radar (Radar), 2021. doi:10.1109/radar53847.2021.10028597
[22]. L. Li, X. Xu, and F. Li, "Towards super-resolution microwave imaging: General framework," ISAPE2012, 2012. doi:10.1109/isape.2012.6409015.
[23]. K. Thomson-Jones, "Digital Imaging Technology," Image in the Making, pp. 1–31, 2021. doi:10.1093/oso/9780197567616.003.0001.