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Pavement Crack Monitoring: Literature Review

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ABSTRACT

Crack monitoring of pavements is an ever-evolving technology with new crack identification technologies being introduced frequently. Although older technologies consisted of physical removing the pavement section using coring, however new methods are available that are non-destructive and yield a higher performance than conventional technologies. This paper compiles various crack monitoring technologies such as wireless sensor networks, photo imaging, laser imaging, 3D road surface profile scans, acoustics wave propagation technology, embedded strain sensors and onboard vehicle sensors that majorly use an artificial intelligence algorithm to identify and categorize the cracks. The research also includes the use of convolutional neural network that can be used to analyze pavement images and such neural network can localize and classify the cracks for crack initiation and propagation stage. The research concludes with the favor of using the optical imaging technology called Syncrack which serves better performance in terms of time of prediction by 25% and accuracy by 30% when compared to other sensing technologies.

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1. Introduction

Road infrastructures require regular maintenance to provide and preserve users' usability, accessibility, and safety. For the past decades, the annual tremendous expense has been spent on maintenance and upgrades of existing road infrastructures in the world. In order to make best use of the limited fund and preserve the serviceability of the road network to the maximum extent, the road managing agencies must optimize the maintenance scheme according to the actual distress status of the road infrastructures. Rising in response to the practical requirements, pavement health monitoring is applied to timely collect and evaluate the damaged states of road infrastructure. Advanced and effective monitoring systems have been developed and widely applied in management of road infrastructure. Road health monitoring has gone from manual and destructive methods through automated in vehicle equipment to the most recent wireless sensor network (WSN), embedded into the pavement (Di Graziano et al., 2020).

Evaluation of the distress condition of a road structure has widely been indicated with a numerical value in the rating system of pavement distress. All of the distresses in pavement structure are categorized into different

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classifications, for each class of distress, two numbers are assigned to any distress instance, one number is the weight factor of this distress class signifying the relative effect of it among all of the distress types on the damage condition of the pavement structure, another number indicating the severity of this distress instance. Summation of the respective products of two numbers attains a number ranking the damage status of the designated road section. The damage rank is an important reference for the road managing agency to work out the optimum maintenance and rehabilitation plan for their jurisdictional traffic infrastructure. with the rapid development of pavement theory and engineering practice, various evaluating systems for road damage (Alavi et al., 2016; Okine & Adarkwa, 2013; Quarles, 2017; Rodés et al., 2020; Wang & Elliot, 1999).

Crack is one of the common distresses in asphalt pavements. Crack not only harms the integrity, decreases the serviceability, and reduces the bearing capacity of asphalt pavements, but also develops passages for hazardous matters (such as moisture, chemicals, corrosive gases, etc.) to intrude into the pavement structure, which would accelerate the failure of asphalt pavements. So, timely repairing or sealing of cracks is crucial to maintain serviceability and achieve the service life of asphalt pavements. Real-time inspection and accurate prediction of the cracking condition of pavements are the prerequisites to working out cost-efficient maintenance or rehabilitation scheme for pavement structures.

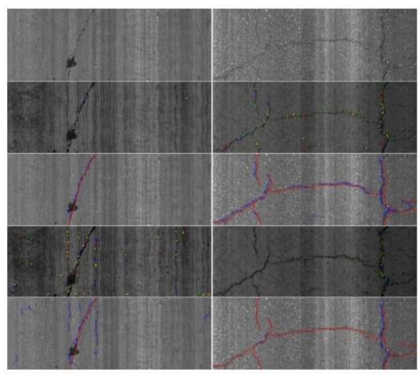


Fig. 1. Crack detection using optimized machine learning through optical imaging. Taken from (Gavilán et al., 2011)**.**

The use of machine learning algorithms through optical imaging for identifying and classifying cracks has been shown (see Fig. 1). For decades, amounts of research on the monitoring and prediction of the crack in pavement have been carried out and remarkable findings have been obtained (Bao et al., 2016; Fan et al., 2018; Rill-García et al., 2022; Yang, 2014). The drawback of using machine learning optical imaging is the development of each algorithm based on different geographic area of pavement. Since cracks can have different types of shapes and orientations, therefore the artificial intelligence algorithm would keep on requiring further modifications.

There has been a common view that the evolution of cracks comprises of crack initiation and crack propagation. Crack initiation characterizes a certain damage stage of pavement structure, before which the pavement structure full of micro cracks can still be addressed as a continuum and fracture mechanics is inapplicable to the analysis of the pavement structure. From the nominally intact status to crack initiation, three is a period of time for micro cracks to grow and coalesce into macro cracks. Starting from the crack initiation, macro cracks would propagate complying with fracture mechanics. So, the lifespan of pavement structure is usually composed of the life of crack initiation and the one of crack propagation (Bao et al., 2016).

The stage of crack initiation is generally considered a progressive process of damage, which is from intact structure to the emergence of macro cracks in pavement structure. During the crack initiation, the micro cracks coalesce into macro cracks, thereafter, crack propagation starts. The internal damage evolution of the pavement structures is an invisible deterioration process, crack initiation is relatively more difficult to monitor and predict, namely, the severity of internal damage in pavement structure is difficult to track. External observation cannot acquire the desirable result in monitoring or prediction of crack initiation, internal sensing with embedded sensors in pavement structures is a promising method for detection of crack initiation inside pavement structure. Publications on monitoring of crack initiation are relatively very few (Fedele et al., 2017).

In most of the retrieved literature, efforts of crack detection are mainly dedicated to the geometric feature extraction, classification, and severity evaluation of the surface cracks in the pavement structure. It is the periodical monitoring of macro crack propagation, which belongs to the external observation and the research findings which have been published relatively more (Al-Qadi et al., 2010; Ma et al., 2022; Sun et al., 2020).

2. Monitoring of crack propagation

Crack is a common kind of distress, and is usually classified into different types: transverse crack, longitudinal crack, alligator crack and block crack. Different types of cracks originate from different mechanisms, which implicate the corresponding treatment methods. Furthermore, different types of cracks damage the pavement structure with various extents. In the retrieved literature, the vast majority of the research on the monitoring of crack in pavements focus on how to quickly identify the type and evaluate the severity of cracks in the pavement structure. For this purpose, technologies for extracting the features and algorithms for automated classification of surface cracks have been developed (Khamlichi et al., 2017; Zuo et al., 2008).

The earliest way to detect cracks in pavement is manual observation, in which inspectors walk along the pavement sections while measuring and noting the relevant information of the cracks. Manual survey is inefficient and time consuming. This is a subjective method easily bringing forth inconsistency among the data collected by different surveyors. Meanwhile, manual inspection along the pavements could disturb the traffic and incur risks to the inspectors (Pérez-Jiménez et al., 2022; Zhou & Song, 2021).

To improve the work efficiency and the objectivity of the data collected in crack detection, automated method has superseded manual method to overcome the disadvantages of manual surveys. In the retrieved literature, researches on the automated detection of road cracks have centered on the technologies in automated acquirement and process of the crack images. With the development of image acquisition technology, from photography to 3D laser scanning technology, quick capturing the detailed image of surface cracks is not a difficult task any more. Extracting sufficient and accurate information from the crack images, namely image processing technology, has gone through manual stage, semi-automatic stage and automatic one. The crack images are usually contained in a big panoramic picture of the pavement surface. Ever since 1999, researchers have devised means for remotely monitoring the surface profile of pavements and thus identify the cracks on the pavements using onboard laser sensors on moving vehicles. The system developed by Komatsu to identify and monitor the occurrence of distress such as cracks in the pavements has been shown (see

Fig. **2**) (Wang & Elliot, 1999).

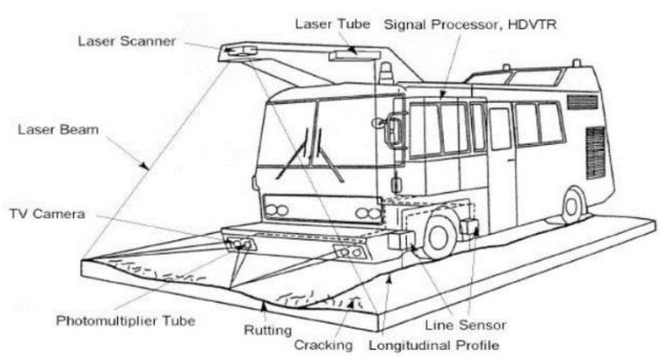
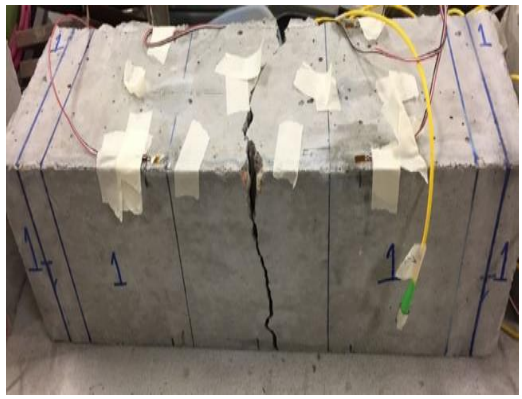


Fig. 2. Use of line scanner and laser beam and camera for optical image processing. Taken from (Wang & Elliot, 1999)**.**

Extracting the crack information from the images is a multidisciplinary technology, in which the knowledge of pavement engineering and pattern recognition are used. During the development of the crack image processing technologies, various algorithms for automated crack detection have continually been put forward through applying mathematical theories, physical technologies, information technologies and computer technologies. The corresponding literature has emerged in large numbers.

For decades, diverse semi-automated destructive or automated nondestructive testing techniques have been developed, such as charge-Coupled Device, Ground Penetration Radar, supersonic wave, Laser Systems and Hybrid systems, etc. (Alinizzi et al., 2017; Canestrari & Ingrassia, 2020; Gavilán et al., 2011; Gehri et al., 2020; Subirats et al., 2015; Zuo et al., 2008). However, GPR and charged coupled device are unable to provide accurate orientation of cracks in the pavement. Nevertheless, in application of these techniques to crack detection, their disadvantages manifest and await to be overcome respectively. (Alshandah et al., 2020) have successfully developed the mechanism, for integration of strain sensors embedded in the pavement for detecting occurrence and propagation of cracks. The setup of sensors and induced crack in the concrete block is shown (see Fig. 3).

Fig. 3. Development of strain sensors for crack detection. Taken from. (Alshandah et al., 2020)**.**



For automated detection of crack, due to the irregularities of pavement surfaces, successful detecting, classifying, and quantifying cracks from the images demands complex algorithms based on all sorts of mathematical theories and computer techniques (Alshandah et al., 2020; M. T. Cao et al., 2021; Iodice et al., 2020; Lau et al., 2020; Praticò et al., 2020; Xiao et al., 2017; B. Zhang & Liu, 2019).

. (M. T. Cao et al., 2021) have summarized the methods in automatic crack detection into three groups, which are Image Acquisition Group, Image Processing Group and Image recognition group. Smart flying robot for image acquisition can work autonomously with low cost and high speed, but could be replaced by experts in the near future. In Image Processing Group, image processing method plays a central role in pavement crack detection and classification. Image processing can be subdivided into six sub steps: pre-processing segmentation, feature extraction, feature selection, detection, classification. However, the embedded strain sensors lack behind other crack detection technologies in terms of longevity and destructive nature of operation. Moreover, any fault in the embedded sensor would lead to higher maintenance costs.

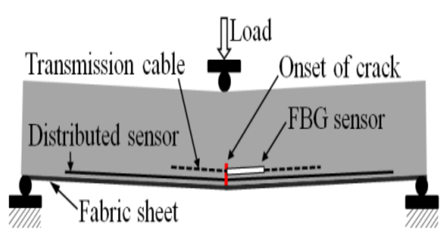


Fig. 4. Setup of crack detection system using FBG sensors. Taken from. (Bao et al., 2016)**.**

Setup of strain sensor in the bottom of asphalt beam for measuring the propagation of cracks as a result of repetitive loadings is presented (see

Fig. **4**). The acquired pavement images contain miscellaneous unwanted objects, an effective preprocessing step is vital for obtaining good results. Pre-processing is related to accentuation of the crack features and reduction of background interference. Image segmentation is a process to extract the region of interest from the image. The optimization algorithm used for image processing for detection of cracks is shown (see

Fig. **5**).

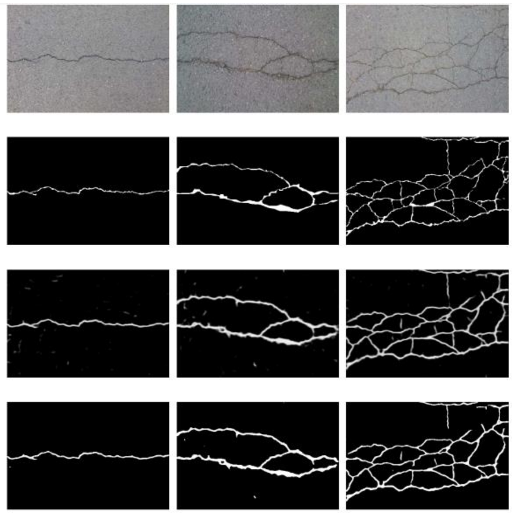


Fig. 5. Crack detection using ANN through optical imaging. Taken from. (Fan et al., 2018)**.**

Several image segmentation methods have been proposed in publications. Feature extraction from the image is the goal of image processing. Most of the existing feature extraction techniques are totally used for boundary extraction and spatial feature extraction. Feature selection approaches are categorized into three types: complete search, heuristic search and random search. Detection is to isolate the crack from the pavement image. There are three types of methods for crack detection: unsupervised, supervised and semi-supervised. Classification is to distinguish the variance between crack and non-crack regions. Diverse classification approaches have been proposed for different applications. In the image interpretation group, there have been several methods to evaluate the severity and extent of the classified cracks.

In the field of optical imaging, (Naddaf-Sh et al., 2019) have introduced a revolutionary method that uses convolutional neural network for classification of cracks based on their severity. Data is collected using optical imaging cameras mounted on the moving vehicle and onboard systems can classify cracks with 97% accuracy with speeds of upto 11.1 km/hr. Moreover, (Zhou & Song, 2021) have proposed a 3D laser imaging system that classifies the cracks based on their vertical projection as observed with the laser transmitter. However, this method is time consuming in terms of data collection and classification of cracks when compared to the method proposed by (Naddaf-Sh et al., 2019). Moreover, (Sollazzo et al., 2016) have introduced a quicker pavement image data collecting technique by using onboard 3D pavement imaging sensors that can record the data with vehicle speed of upto 100 km/h. This results in faster data collection and imaging processing thereby saving time and being useful for highway lengths greater than 500 km.

The above-mentioned research findings from (Bao et al., 2016; T. Cao et al., 2019; Fan et al., 2018) belong to the external crack detection, which is an essential component of pavement distress convey. In order to real-time track the crack propagation and continuously acquire the crack state in the pavement structure, the smart sensor system embedded in the pavement has been developed and applied in crack detection. The embedded sensor can monitor the concealed cracks inside the pavement structure.

Bottom-up crack at its beginning stage is a kind of concealed crack. (Hasni et al., 2017) proposed a self-powered wireless surface sensing approach for the detection of bottom-up cracking in existing asphalt pavements. in this research, FE model was established to simulate the bottom-up crack propagation. With the increasing number of vehicular loading, the surface strain would change with the propagation of the bottom-up crack. In the field, a self-powered wireless sensor grid was embedded into the pavement surface, the in-site surface strain was continuously detected from the sensor grid. However, self powered sensors lack behind other technologies in terms of their destructive nature of monitoring road health. Setup of bottom-up crack monitoring and propagation as induced in the pavement is shown (see Fig. 6).

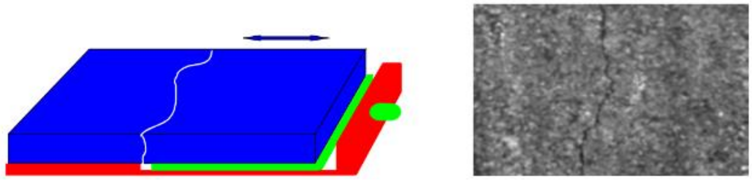


Fig. 6. Use of wavelet transform method for crack monitoring. Taken from. (Subirats et al., 2015)**.**

The changing profile of the in-site strain was compared with the varying strain in the FE model simulation, then, the initiation and propagation of bottom-up crack can be predicted based on the changing profile of the surface strain detected by the sensor grid. The findings in from (Subirats et al., 2015) are useful for monitoring the time of crack initiation, but the position of crack initiation is artificially preset. So this method is not favorable for continuous evaluation of crack propagation.

A smart sensor network is an embedded Wireless Sensor Network (WSN) made by a set of sensors, integrated into the structure of interest in predetermined positions, to monitor a particular event (e.g., appearance and propagation of concealed cracks) or measure a parameter (temperature, pressure, etc.) continuously and in real time, wireless communicating with the Node of computation and/or storage functions, computation or storage Nodes are integrated with antennas for data transmission, allowing remote monitoring. However, the use of WSN is destructive in nature and any malfunction in the WSN equipment may result in costly maintenance costs.

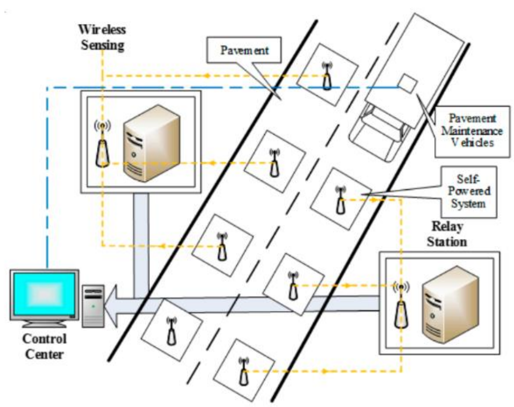


Fig. 7. Setup of a wireless sensor network. Taken from (Xiao et al., 2017).

Smart networks are designed to be self-powered and to optimize energy efficiency and sensing capabilities (see Fig. 7). Application of WSN for pavement monitoring is still undeveloped, its advantages and limitations need to be in-depth investigated with amount of application instances (Cafiso et al., 2020).

(Lan et al., 2011) made experimental verification that the environmental temperature substantially influences the detection result of the pavement roughness with vehicle-based vibration sensor. An automated crack detection system was constructed, which is a vehicle equipped with line scan cameras, laser illumination and acquisition HW-SW, to store and process the digital images for identification of road cracks (Gehri et al., 2020); to boost the accuracy of road crack detection by image processing , wavelet transform and grey level technology was combined to process the image of road surface (T. Cao et al., 2019); fractal theory was applied in image processing of road surface crack, fractal theory-based algorithm could effectively extract the features of road surface crack. Moreover, out of all these aforementioned techniques, the use of line scanners is quite costly compared to the use of optical imaging technique.

3. Monitoring of crack initiation

Crack initiation or onset of the macro crack propagation is the outcome of damage accumulation in the pavement structure, usually manifested as the process that micro cracks emerge and coalesce into macro cracks. Crack initiation signifies a certain damage state of the pavement structure, showing the decreased modulus or increased deformation. Degradation of the pavement properties is a slow damaging process inside the pavement structure and has no visually observable change of outer appearance. When the deterioration develops to a critical status, visible macro cracks would appear in the pavement structure, marking the beginning of the crack propagation (Canestrari & Ingrassia, 2020; Chapeleau et al., 2017).

After the crack initiation, the integrity of the pavement structure is undermined and the hazardous substances from surrounding environment get the passages to intrude into the pavement structure, therefrom, the pavement deteriorates faster than before, which is the main perpetrator of premature failure of pavement. Therefore, the use of Raleigh Wave method comes into consideration for detection of crack and its depth using acoustic signals (see Fig. 8)(Iodice et al., 2020). However, the wave propagation methods lack accuracy due to unfiltered noise in the pavement structure and it is costly to use the equipment that can filter out the noise.

Fig. 8. Use of Raleigh Wave method for detecting crack propagation. Taken from. (Iodice et al., 2020)**.**

Research on the monitoring of crack propagation in pavement is briefly reviewed in the last section. To maintain the serviceability and achieve the design service life of pavement structure, predication and prevention of emergence of cracks in pavement is more efficient than monitoring and sealing of macro cracks. That is to say, monitoring and delaying crack initiation is a proactive measure in the maintenance and management of pavement.

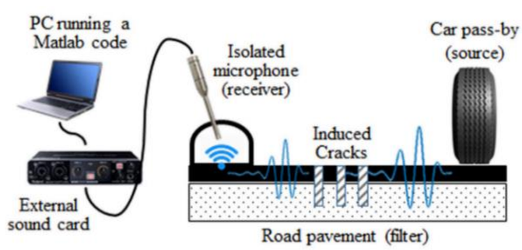


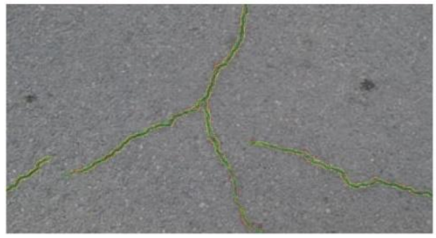
Fig. 9. Crack detection mechanism using vibro acoustic signals. taken from (Praticò et al., 2020)**.**

The mechanism developed to track the propagation of cracks using vibro acoustic signals is shown (see Fig. 9). Tracking the deterioration process and predicting the crack initiation can provide factual information for the optimum pavement preservation scheme. Nevertheless, evolution of internal damage into the emergence of macro-crack is a slowly gradual process of continuous deterioration of pavement performance under the vehicular loading and environmental factors. There is usually no Macroscopic visible manifestation during the deterioration process. For monitoring the deterioration of pavement structure, monitoring devices must be embedded into the pavement body to sense the changing responses under the continuous action of vehicular loading and environmental factors.

Through the combination of theoretical derivation and experimental calibration, the changing pattern of the sensed responses, such as strain, stress, deformation, moisture, and temperature, etc. could be projected to the evolution law of certain damage quantities which quantitatively characterize the damage state. however, the pavement structure is three dimensions, it is unrealistic to fill the whole pavement body with monitoring devices; properties of the pavement structure are not ideally homogeneous and different parts of the pavement are subject to the different degree of external action, the deteriorating rates in different places of the pavement structure are also unequal, meaning that the position and time for the earliest crack initiation are stochastic phenomena.

Determining the monitoring positions and the number of monitoring devices is a difficult problem. An example of the use of modern day Syncrack tool used for automatically identifying and classifying cracks using optical imaging is shown (see

Fig. 10) (Rill-García et



al., 2022).

Fig. 10. Use of Syncrack generator for automatic crack detection. Taken from (Rill-García et al., 2022)**.**

So, Long-term and all-weather continuous Monitoring of the internal damage evolution is much more demanding and challenging than the external monitoring of crack propagation.

In continuous damage detection, the embedded sensors must be compatible with the heterogeneous nature, and mechanical properties of pavement materials. Firstly, the sensors should be as small as possible so that they are not so intrusive in the pavement layers. Secondly, for strain measurements, stiffness of the sensors has to match that of the pavement materials in order to measure correctly the mechanical properties of the pavement. Moreover, the embedded sensors must withstand the stresses experienced during the pavement construction process (high temperature and compression). After that, if a long term monitoring is implemented, the sensor should be resistant to corrosion and thermal-mechanical coupling fatigue a (Chapeleau et al., 2017).

(Fedele et al., 2017) proposed a way to detect the concealed crack (such as the bottom-up crack). The pavement structure was taken as a vibro-acoustic filter, the vibration source could be travelling vehicles or environmental vibration and the excited vibration in pavement would emit sound, which is captured by the receiver. The received sound signature carries information of the pavement distress including concealed crack. Through complex algorithms, the data of the concealed crack can be extracted from the sound signature. However, a complete algorithm must be designed again for a pavement structure with different mechanical properties.

For prediction and prevention of crack initiation, real-time continuous monitoring of the damage state of asphalt pavement structure is an effective means. Throughout the retrieved literature, Due to the complexity of this issue, current research findings are at the preliminary stage. In order to be universally practical, real-time continuous monitoring of the damage state should be integrated into the smart material technologies.

4. RESEARCH WORK SUMMARY

Summary of research work is presented here. (See Table 1).

Table 1. Summary of research work on crack monitoring

Researchers, Year	Mechanism	Mode of testing	Stage	Remarks
(Wang & Elliot, 1999)	Survey vehicles with mounted cameras	Non destructive	Crack identification, initiation and propagation	Use of close circuit cameras and scanners for identifying and classifying cracks
(Zuo et al., 2008)	Use of optical image processing for edge crack detection in pavements	Non destructive	Crack propagation	Pavement edge crack detection using image segmentation method
(Lan et al., 2011)	Wireless Sensor Networks (WSN) with strain gauges	destructive	Crack propagation	Crack detection as a result of temperature changes in pavement
(Gavilán et al., 2011)	Use of mounted line scanners and laser	Non destructive	Crack propagation	Identification and classification of cracks using laser illumination and

Researchers, Year	Mechanism	Mode of testing	Stage	Remarks
	cameras for crack detection			line scan cameras
(Grellet et al., 2012)	Optical imaging	Destructive	Crack initiation and propagation	Use of optical imaging and fiber optic strain plate for positioning of cracks
(Zou et al., 2012)	Optical imaging with AI algorithm	Non destructive	Crack initiation and propagation	Development of AI algorithm for detection and classification of cracks from pavement images
(Wang et al., 2014)	3D laser imaging	Non destructive	Crack initiation and propagation	Use of vehicle mounted 3D laser transmitters for detection of cracks and road surface defects
(Zalama et al., 2014)	Vehicle mounted LIDARS and Cameras	Non destructive	Crack initiation and propagation	Use of onboard laser sensors and optical imaging cameras for crack detection
(Subirats et al., 2015)	Optical Image processing for crack detection	Non destructive	Crack initiation and propagation	Use of wavelet transform for automatic crack detection in pavements
(Sollazzo et al., 2016)	Optical imaging with 3D pavement data	Non destructive	Crack initiation and propagation	Use of onboard 3D scanners for identification and classification of cracks at speeds of upto 100 km/h.
(L. Zhang et al., 2016)	Convolutional neural network with optical imaging	Non destructive	Crack initiation and propagation	Development of convolutional neural network form classification of optical imaging data
(Wu et al., 2016)	Optical imaging defragmentation	Non destructive	Crack propagation	Development of artificial neural network with image defragmentation technique for detection of road surface cracks using optical imaging
(Bao et al., 2016)	Fiber Bragg Grating (FBG) strain sensors	destructive	Crack initiation	Use of FBG strain sensors for identifying micro and major cracks in pavements
(Alavi et al., 2016)	RFID tagged sensors	destructive	Crack initiation	Crack monitoring as a result of fatigue cycles
(Chapeleau et al., 2017)	Use of fiber optic sensors for crack detection	Non destructive	Crack initiation and propagation	Use of fiber optic sensors based on Rayleigh scattering for crack detection under tire loading
(Xiao et al., 2017)	Piezoelectric sensors for crack monitoring coupled with strain gauges	destructive	Crack propagation	Use of self-powered sensors for measuring strain and detection of cracks
(Alinizzi et al., 2017)	Optical image processing using optimized Artificial Neural Network (ANN)	Non destructive	Crack initiation and propagation	Development of optimized Machine Learning algorithm for crack classification under wheel loading
(Fedele et al., 2017)	Acoustic signature detection	Non destructive	Crack initiation and propagation	Acoustic wave detection using microphone receivers
(Cubero-Fernandez et al., 2017)	Optical imaging and AI	Non destructive	Crack initiation and propagation	Detection of cracks using image processing AI algorithm
(Fan et al., 2018)	Optical imaging using Artificial Neural Network (ANN)	Non destructive	Crack initiation and propagation	Development of ANN to identify and classify the cracks using optical imaging
(Fay et al., 2018)	Optical imaging	Non destructive	Crack initiation and propagation	Detection of cracks after water induced damage in pavements
(Maeda et al., 2018)	Optical imaging with ANN	Non destructive	Crack initiation and propagation	Use of vehicle mounted optical imaging sensors coupled with artificial neural network for crack detection on the move
(Y. Zhang et al., 2018)	Infrared imaging	Non destructive	Crack propagation	Use of infrared imaging sensors mounted onboard of the moving

Researchers, Year	Mechanism	Mode of testing	Stage	Remarks
				vehicle for crack detection
(T. Cao et al., 2019)	Image processing for crack detection	Non destructive	Crack initiation and propagation	Use of fractional differential and fractal dimension for optimizing image processing of cracks
(B. Zhang & Liu, 2019)	Point cloud data and optical imaging for crack monitoring	Non destructive	Crack initiation and propagation	Use of Artificial Intelligence for detection of cracks using optical images
(Naddaf-Sh et al., 2019)	Optical imaging with Convolutional Neural Network	Non destructive	Crack initiation and propagation	Classification of cracks with convolutional neural network and optical imaging with vehicle mounted cameras
(Di Graziano et al., 2020)	Wireless Sensor Networks (WSN) with strain gauges	destructive	Crack initiation	damage detection due to fatigue cracking in pavements
(Cafiso et al., 2020)	Ground Penetrating Radar (GPR)	Non destructive	Crack initiation and propagation	Microcracks detection in pavement structure
(Canestrari & Ingrassia, 2020)	Strain gauges doe determining top-down cracks	destructive	Crack propagation	Modelling of strain gauges for determining top down cracking in pavements
(Gehri et al., 2020)	Optical imaging and prediction of crack types using ANN	Non destructive	Crack propagation	Development of automatic crack detection and data acquisition system using ANN
(Alshandah . et al.,2020)	Strain gauges for bottom-up crack detection	destructive	Crack initiation and propagation	Crack propagation using strain gauges for bottom up crack detection
(Iodice . et al., 2020)	Digital image processing using wave decomposition method for crack detection	Non destructive	Crack initiation and propagation	Use of wave decomposition method for determining crack depth and propagation
(Lau. et al., 2020)	Optical image processing using ANN	Non destructive	Crack propagation	Optimization of crack detection and classification using U-Net based ANN
(Praticò. et al., 2020)	Acoustic waves for crack detection	Non destructive	Crack initiation	Use of machine learning method for detection and classification of cracks using vibro acoustic signature
(Lee. et al., 2021)	Vibration detection under moving load	Non destructive	Crack initiation and propagation	Road smoothness detection using optical imaging and accelerometers
(Zhou. et al., 2021)	3D laser imaging	Non destructive	Crack initiation and propagation	Use of 3D laser imaging for identifying and classifying road surface cracks
(Chen. et al., 2021)	Optical imaging	Non destructive	Crack initiation and propagation	Use of time frequency analysis and convolutional neural network for crack detection in pavements
(Abbas. et al., 2021)	Optical imaging	Non destructive	Crack propagation	Identification and detection of cracks and potholes using onboard cameras
(Safaei. et al., 2021)	Optical imaging with pixel segmentation	Non destructive	Crack propagation	Development of AI algorithm with pixel segmentation technique for detection and classification of cracks using 2D images
(Ma. et al., 2022)	Optical imaging	Non destructive	Crack propagation	Development of convolutional neural network for robust crack detection of asphalt and concrete pavement surface
(Rill-García. et al., 2022)	Optical imaging using synthetic generation algorithm	Non destructive	Crack initiation	Crack identification and classification using synthetic generation software “Syncrack”
(Chen. et al., 2022)	RGB thermal imaging	Non destructive	Crack initiation and propagation	Development of ANN (Artificial Neural Network) with RGB thermal

Researchers, Year	Mechanism	Mode of testing	Stage	Remarks
				imaging for detection of cracks and defects

5. CONCLUSIONS

Crack in asphalt pavement structure is a common distress and one of the critical factors expediting pavement failure. Monitoring of cracks in asphalt pavement is a major task of pavement managing agencies. Prediction or prevention of crack initiation is a kind of proactive maintenance measure, which is more efficient and economical than sealing the existing cracks. Among the various crack detecting methodologies, the optical imaging technology provides a better performance in terms of time of detection and accuracy in categorization of cracks. However, the most prevalent technology with right amount of procedural help available is the Syncrack tool. The Syncrack tool uses the artificial intelligence algorithm with locally made synthetic generation software to seed up the crack detection process. Moreover, the Syncrack tool classify the cracks according to the crack width and its spread from low to high level warning. This classification can help the highway maintenance agencies to efficiently allocate the rehabilitation funds based on the severity of cracks. The following are some of the conundrums.

1. Quantitative sign of crack initiation

Besides modulus, more variables characterizing the internal damage state need to be explored. crack initiating mechanism needs to be further investigated specifically. The critical state of crack initiation should be clarified and defined, being quantitatively indicated. Since the wireless sensor networks rely on the change in load response from the embedded sensors, the quantitative measurement needs further refinement. The load response would need further calibration based on type of the sensor being used. Therefore, embedded sensors are only suitable for sections of the pavement with identical mechanical properties.

2. Size, number, position of the sensors

Pavement structure is a continuously spatial body. It is impractical to continuously fill the pavement structure with sensors. Then, how are the positions of embedded sensors determined. A proper size of the individual sensors is necessary to ensure the required precision accuracy of the measure. Therefore, wireless sensor networks that use embedded sensors to calculate load response provide only a temporary solution and are costly when compared to the optical imaging or vibroacoustic technology. However, the embedded sensors are destructive in nature and any kind of malfunction in the embedded system can be difficult to diagnose and expensive to repair.

3. Viability of the sensors

For the new pavement structure, the embedded sensors must sustain both the construction load and the operation load, including the varying temperature, moisture and chemical reactions. Encapsulation of sensors can effectively shelter from the outer hazardous factors, but usually reduces the sensitivity of the sensors. However, maintenance of these sensors for a longer period of time can become a financial challenge. Since the wireless embedded sensors are destructive in nature, future reconstruction of pavement will require extra costs for removal and reinstallation of embedded sensors.

4. Storage, transmission, and process of massive data

Continuous monitoring of the pavement structure with pervading embedded sensors produces overwhelmingly large amount of data, which is a challenging task for data storage schemes. Transmission of massive data also presents a huge challenge. Process of huge amounts of data and extraction of the required information from the data are calling for innovative techniques. Therefore, optical imaging technology offers a cost-effective alternative solution for storing a large amount of data usually in the cloud.

5. Self-powered operation of the sensor system

The operation of the embedded sensor system should run with low energy consumption, which can diminish the thermal effect. Self-adjusted electricity current in reaction to the operational tempo of the sensor system can minimize the negative effect. Self-powered sensor system is a promising solution to the energy supply of continuous monitoring. Since, it is an embedded sensor, any kind of maintenance needed would render this sensor expensive for crack detection and monitoring.

6. Smart pavement constructed with smart materials

The final solution to the above problems is smart pavement. Through imposed alteration to the properties of material, the material would acquire certain autogenous functions. Some additives can be mixed into the material matrix so that the material can obtain some autonomous functions. Some smart materials with power selfgenerating, damage self-healing, and distress self-detecting functions have become interesting research subjects. Self-healing can be further monitored with the load response from embedded sensors. The load response from the sensors can show proper functioning of self-healing pavements. However, any kind of maintenance issues would render this option expensive.

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