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Research Progress on Concrete Crack Monitoring and Self-Healing Technologies

Bowen Chen, Shan Zhu, Fengyu Yang

College of Construction Engineering, Jilin University, Changchun 130026, Jilin, China

Abstract: ***This paper provides a systematic overview of recent advances in intelligent monitoring and self-healing technologies for concrete cracks. In terms of monitoring, laser scanning combined with AI-based image recognition enables high-precision crack classification using 3D point clouds and deep learning algorithms. Wireless sensor networks based on the Internet of Things (IoT), integrated with fiber Bragg grating and edge computing, support real-time dynamic monitoring and risk assessment. Phased array ultrasonic technology locates cracks with depths ≥5 mm through beam synthesis and image reconstruction algorithms. On the self-healing front, microbial-induced calcite precipitation (MICP) utilizes alkaliphilic bacteria to produce calcium carbonate crystals, effectively repairing cracks up to 0.52 mm wide. Shape memory alloys (SMAs) close cracks through phase transformation-induced stress, increasing healing efficiency by 40%. Microcapsule-based systems release encapsulated agents that initiate crystallization reactions, enabling the healing of 0.23 mm cracks within 3 days. However, several technical challenges remain: monitoring systems are costly and environmentally limited, and the effectiveness of self-healing technologies significantly decreases with increasing crack width, leading to reduced long-term performance. Future efforts should focus on the integration of intelligent technologies, materials innovation, and sustainable development to address the trade-off between performance and cost. This review aims to provide a theoretical foundation for the construction of intelligent, self-healing concrete systems.***

Keywords: Concrete, Crack, Intelligent Monitoring, Self-Healing Technology, Microbial Repair.

1. Introduction

Concrete cracking is a common manifestation of durability degradation in engineering structures. However, traditional repair methods often suffer from delayed response, high costs, and limited ability to detect internal cracks. In recent years, advancements in crack monitoring technologies and breakthroughs in self-healing materials have provided promising solutions to these challenges. Real-time monitoring systems based on optical fiber sensing, laser scanning, and the Internet of Things (IoT) can accurately identify the initiation and propagation of cracks. Meanwhile, self-healing technologies such as microbial mineralization and microencapsulation simulate biological mechanisms to achieve autonomous crack repair. The integration of intelligent sensing and self-healing technologies significantly enhances the controllability and performance of concrete structures throughout their service life. According to preliminary statistics, smart concrete incorporating both monitoring and self-repair capabilities is rapidly transitioning from laboratory research to practical applications, emerging as a vital direction in the development of novel construction materials. This review systematically analyzes the interplay between innovations in monitoring techniques and the development of self-healing materials, aiming to provide theoretical support for the establishment of an intelligent crack prevention and control system.

2. Concrete Crack Monitoring Technologies

2.1 Laser Scanning and AI-Based Image Recognition

The integration of laser scanning and image recognition for crack monitoring utilizes multidimensional data fusion and intelligent algorithms to identify structural damage in concrete. The approach is founded on high-resolution laser scanning coupled with machine learning techniques. High-frequency laser pulses acquire millimeter-level resolution 3D point cloud data, while edge detection (e.g., Canny algorithm) and threshold segmentation extract geometric features of cracks. Ge et al. [1] employed a phase-shift terrestrial laser scanner (FARO Focus3D S120) to collect 3D point clouds and proposed a method combining k-nearest neighbors (kNN) and principal component analysis (PCA) to calculate point normal variance. This, together with the alpha-shape algorithm, enabled automatic separation of cracks from surface pits. The accuracy of crack size measurements, validated by projection and skeletonization algorithms, reached 0.003 mm, with measurement deviations within 5% of manual results. Song et al. [2] validated the method using multi-view 3D laser scanning, achieving accurate classification of 0.02 mm cracks and forecasting crack propagation trends via convolutional neural networks (CNNs). Liu et al. [3] applied CNNs in tunnel construction in Chongqing, achieving a 95% recognition rate for longitudinal cracks. The implementation process typically involves: (1) establishing standard reference points using total stations, (2) capturing 3D data via UAV-based scanning, (3) filtering point clouds using ISS algorithms to build a DEM and geo-annotated images, and (4) generating an XML-based crack parameter report. Real-world applications confirm the method's high resolution (0.02 mm), improved crack recognition (40% increase), and reduced maintenance costs (30%). Its all-weather operation, compatibility with varied materials, and traceable data outputs offer a robust digital solution for infrastructure health monitoring.

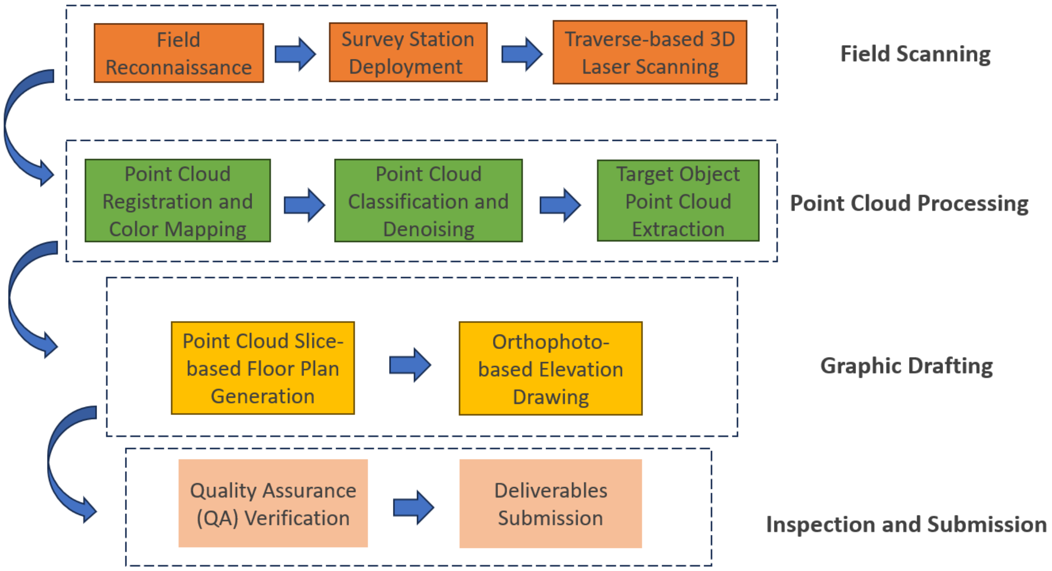


Figure 1: Key Workflow of 3D Laser Scanning Operations

2.2 Construction of Multi-Modal Sensing Networks and Strain Perception

IoT-based wireless sensor networks for crack monitoring utilize multimodal sensing and intelligent platforms to track structural damage dynamically. These systems consist of strain sensing, displacement detection, and data analytics components. Laser displacement sensors and MEMS accelerometers capture displacement variations during crack evolution. Threshold segmentation extracts morphological features, which are wirelessly transmitted to cloud platforms. Classification and risk stratification are conducted using machine learning models such as SVMs and CNNs, enabling prediction of crack propagation trends. Low-power design and energy harvesting capabilities of wireless sensor nodes (SNs) ensure long-term operation in harsh environments. In laboratory settings, the system achieved wireless data transmission and power supply over an 11-meter range within reinforced concrete structures[4]. Lee et al. [5] constructed a crack width prediction model using IoT sensors and the CEB-FIP model, confirming consistency between predicted and observed trends. Huang et al. [6] developed a cost-effective IoT-enhanced monitoring system using an Arduino Nano 33 microcontroller, enabling pavement-wide scanning at 100 km/h with 95% classification accuracy. This closed-loop system, built on "perception-analysis-response," provides an efficient solution for life-cycle infrastructure health management.

2.3 Phased Array Ultrasonic Technology

Phased array ultrasonic crack detection utilizes piezoelectric chip arrays and beamforming techniques. By electronically controlling the excitation timing of each chip, the system dynamically focuses or steers the ultrasonic beam to locate internal defects in concrete with high precision. Based on Huygens' principle, array probes—typically comprising 16 to 128 elements—employ phase delay algorithms to synthesize ultrasonic beams, surpassing the spatial resolution limitations of conventional single-element probes. The technology supports multi-angle scanning and 3D defect imaging.

Xu et al. [7] provided a systematic review of sound field modeling and imaging techniques for ultrasonic phased arrays, offering theoretical support for future developments. Shen et al. [8] developed a low-frequency ultrasonic array device (JL-UCID(B)) featuring dual-ray coverage and dry-point contact (DPC) transducers. This setup enhances image stability under noisy conditions and employs an improved crack-focusing synthetic aperture focusing technique (CF-SAFT) to suppress surface wave interference and achieve accurate SH-wave diffraction focusing. The standard test process involves four main steps (illustrated in Figure 2). Experimental results demonstrate a detection accuracy of ±0.2 mm for cracks ≥5 mm in depth—more than triple the efficiency of conventional ultrasonic NDT. The technology successfully detects bottom cracks in reinforced multi-layer concrete structures and has been applied in the inspection of critical infrastructures such as nuclear containment structures and bridge bearings.

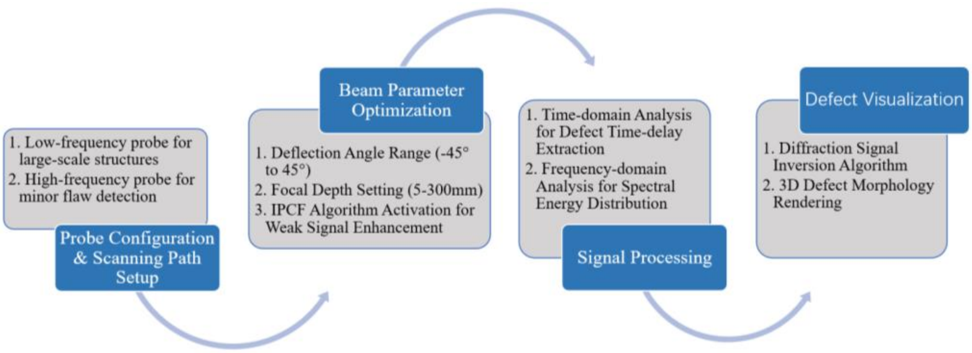


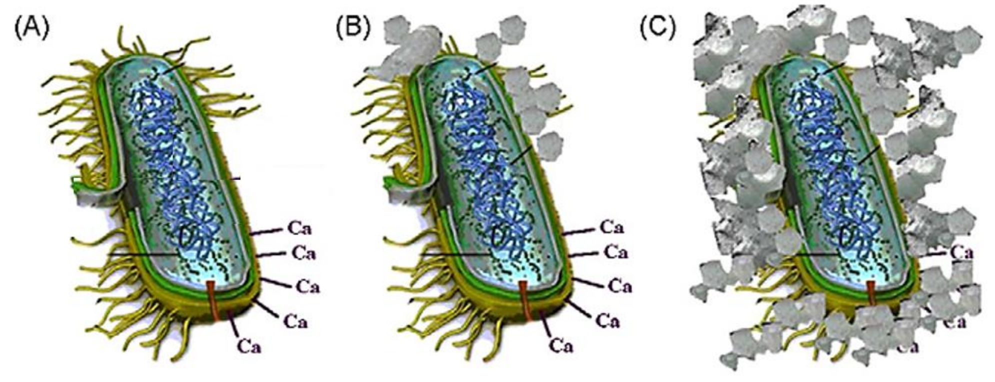
Figure 2: Operational Procedure Flowchart for Phased Array Ultrasonic Crack Detection

3. Self-Healing Technologies for Concrete Cracks

Self-healing technologies, which integrate material science and biotechnology, draw inspiration from biological repair mechanisms to enable concrete to autonomously restore damage or cracks. This approach provides a promising pathway for restoring structural performance. In recent years, self-healing technologies have gained significant attention and have seen rapid development from laboratory research to real-world engineering applications.

3.1 Microbially Induced Calcite Precipitation (MICP)

Microbially induced calcite precipitation (MICP) mimics biomineralization mechanisms to impart self-healing capabilities to cement-based materials. The core principle lies in the coupling of microbial metabolism and the directed deposition of mineralization products. Once activated, alkaliphilic bacteria such as *Bacillus pasteurii* produce urease, which decomposes urea to generate carbonate ions. These ions react with calcium ions in the pore solution to form calcite crystals, thereby sealing cracks and restoring mechanical integrity (see Figure 3 [9]). Functional bacteria are often encapsulated within porous aggregates or biomass fibers to build protective carriers. Numerical simulations by Kou et al. [10] based on a multi-field, multiphase model showed that increasing the initial bacterial concentration by 1.7 times enhanced calcite production by 1.6 times and reduced permeability by 51%, providing theoretical support for engineering parameter optimization. Zhang [11] further confirmed the efficacy of expanded perlite as a carrier, due to its porosity and cellular wall structure, which improved bacterial viability to over 70%. Additionally, surface coating reduced its water absorption from 240% to 30%, significantly enhancing the stability of the repair process. After 28 days of curing, the maximum repaired crack width reached 0.52 mm, with a healing degree exceeding 60%. Du et al. [12] successfully applied MICP-based concrete in underground sidewall crack repair, achieving complete crack closure after 28 days, along with improved impermeability and strength. However, Wei et al. [13] highlighted the dual nature of the technique: while microbial activity delayed initial cracking by 66.7%, it also increased total crack area by 48.6% and crack quantity by 24.6%, suggesting that metabolic byproducts might compromise early-age crack resistance.



(A) Urea Hydrolysis (B) Calcium-Carbonate Ion Complexation (C) Microbial Encapsulation via Carbonate Precipitation

Figure 3: Schematic Diagram of Ureolytic Bacteria-Mediated Biomineralization [9]

3.2 Shape Memory Alloys (SMAs)

Self-healing using shape memory alloys (SMAs) exploits the intelligent response of SMA materials to recover crack-induced damage in concrete. The mechanism relies on the combined effects of the shape memory effect (SME) and superelasticity (SE). Li et al. [14] revealed that constant electric current activation induced stronger recovery stress compared to stepwise current stimulation, as it more effectively triggered austenite transformation. Initial strain and temperature were also found to positively affect recovery force, providing a quantitative foundation for understanding how SMA imparts compressive stress to close cracks. Han et al. [15] developed a strain transfer model to describe the crack healing and monitoring process. They demonstrated that martensite content and embedment length significantly influenced strain transfer efficiency, and that SMA electrical resistance increased monotonically with damage strain in concrete, laying the groundwork for real-time repair monitoring.

Titanium-based SMAs, which allow tunable transformation temperatures through compositional design, are lightweight, strong, and corrosion-resistant—making them suitable for harsh environments. Zhou et al. [16] conducted four-point bending tests on ultra-high toughness cementitious composite (UHTCC) plates embedded with SMA wires. Increasing the SMA wire diameter (2–5 mm) enhanced the crack healing rate from 3.52% to 24.91%. Additionally, applying pre-strain further improved the self-healing performance. Qian et al. [17] reported that incorporating SMA fibers into concrete not only improved tensile and flexural strengths by 27.5% and 40.18%, respectively, but also significantly enhanced the overall self-healing capability, offering new directions for structural crack remediation.

3.3 Microcapsule-Based Self-Healing

Microcapsule-based self-healing is a biomimetic approach in which healing agents are encapsulated in polymeric or inorganic shells and released upon mechanical damage to repair cracks. Xu et al. [18] proposed a novel multilayer microcapsule system (see Figure 4), where nutrients and substrates required by microbes are separated within the shell.

These are only released upon cracking, triggering microbial calcium conversion reactions to form calcite and seal the crack. Liu et al. [19] developed microcapsules using polypropylene as the shell material and toluene diisocyanate (TDI) as the core, prepared via melt dispersion-condensation. These capsules had diameters of 50–150 μm and an encapsulation efficiency of 67.5%, with excellent thermal stability. Incorporating 2.5% of such microcapsules enabled complete healing of 0.23 mm cracks within two days. Zhu et al. [20] studied the influence of capsule size and dosage on release efficiency. Numerical simulations and experiments showed that capsules with diameters of 3.35–4.0 mm released 37% and 10% more healing agent at 3% and 5% dosages, respectively, than smaller or larger capsules, supporting economic optimization in engineering applications. Han et al. [21] used a 2D micromechanical model to analyze the mechanical behavior of microcapsule-based self-healing concrete. The study revealed that increasing capsule diameter or volume fraction enhanced peak load and strain capacity. However, a trade-off exists between stress drop and healing efficiency, requiring careful design.

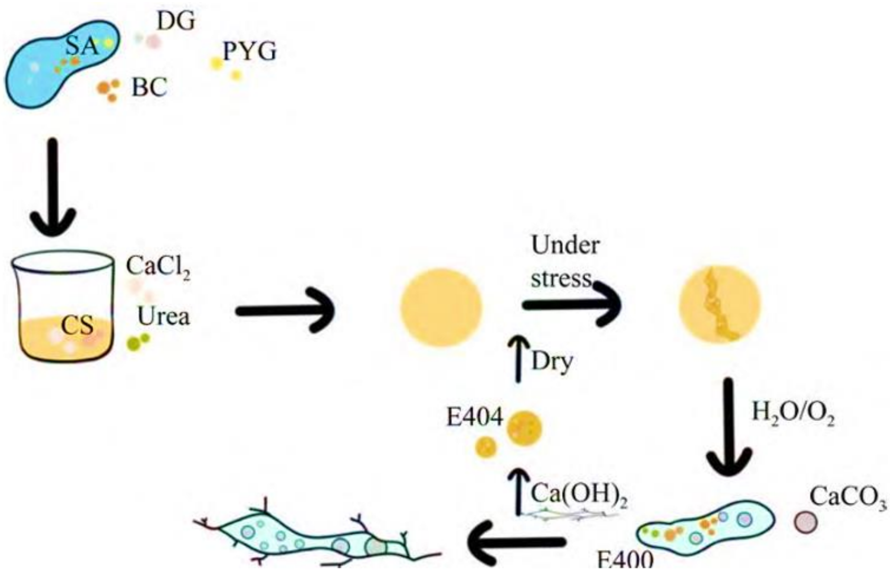


Figure 4: Schematic diagram of microcapsule response repair mechanism.
SA: Sodium alginate; E404: Calcium alginate; CS: Chitosan; E400: Alginic acid; BC: Bacillus cereus; PYG: Peptone; DG: Glycerol [18]

4. Technical Challenges

Despite the significant advancements in crack monitoring and self-healing technologies for concrete, there remain considerable challenges to large-scale implementation. These challenges span from technical limitations in monitoring systems to the reliability and durability of self-healing materials, as well as discrepancies in the pace of development among related technologies.

Firstly, the high cost and complex operation of current monitoring devices significantly hinder their widespread adoption. Instruments such as laser scanners and phased array ultrasonic systems often exceed RMB 100,000 in cost and require professional training to operate, making them impractical for small- to medium-scale projects. Secondly, these systems exhibit poor adaptability in complex environmental conditions. For example, in pavement monitoring at Dublin Airport, low temperatures led to a 30% increase in transmission delay for wireless sensor modules. Similarly, high temperature, humidity, or electromagnetic interference can cause signal instability and data loss. Thirdly, the accuracy of AI-based image recognition for crack detection is still limited. Uncommon crack patterns are prone to misclassification due to the limited size and diversity of training datasets. This calls for the adoption of multi-source heterogeneous data and transfer learning strategies to enhance the generalizability and robustness of detection algorithms. In terms of self-healing, issues of low efficiency and poor long-term performance persist. Both microbial-induced mineralization and microcapsule-based techniques show less than 60% effectiveness in repairing wide cracks, making them unsuitable for large-scale defects. The recovery performance of shape memory alloys deteriorates after repeated phase transitions, and the shell aging of microcapsules leads to an increased leakage rate of the encapsulated healing agents over time. Additionally, microbial metabolic byproducts may adversely affect the ecological compatibility of the self-healing system by lowering the pH of pore solutions, potentially accelerating steel rebar depassivation. Genetic engineering or nanocoatings are therefore needed to improve microbial alkali resistance and compatibility within the cementitious matrix.

5. Future Development Trends

Future research should focus on addressing the current technological bottlenecks by targeting the following key areas:

Firstly, in terms of intelligent technology integration, it is essential to establish a closed-loop system that combines fiber optic sensing networks, microbial self-healing units, and artificial intelligence-based decision-making modules. Such systems would enable full-process automation of sensing, repair, and evaluation, enhancing the intelligence and responsiveness of concrete crack management.

Secondly, material science must break through traditional disciplinary boundaries to drive innovation through approaches such as gene editing and biomimetic design. For example, the CRISPR-Cas9 technique can be used to genetically engineer microbes to enhance the expression of alkali-resistant gene clusters, thereby improving their mineralization efficiency [22]. Additionally, the development of high-performance shell materials—such as nano-modified polymers and composite inorganic materials—can significantly improve the mechanical strength, alkali resistance, and durability of microcapsules in concrete environments [23]. From a sustainability perspective, repair materials derived from industrial by-products have demonstrated notable advantages. Using waste materials such as fly ash and slag as raw materials for microcapsules or microbial carriers in self-healing concrete not only reduces the energy consumption associated with traditional material synthesis but also promotes waste valorization, effectively lowering environmental burdens [24].

6. Conclusion

This paper reviews the integration of crack monitoring and self-healing technologies in concrete, marking a paradigm shift in civil engineering materials from passive maintenance to proactive self-repair. It summarizes the principles and recent advancements of key technologies, including laser scanning, Internet of Things (IoT) sensing systems, microbially induced calcite precipitation, and shape memory alloys. These technologies demonstrate considerable potential for enhancing the long-term durability of concrete and reducing maintenance costs.

However, current limitations persist, particularly in the low self-healing efficiency for wide cracks, the instability of long-term performance, and the challenge of balancing high material costs with the simplicity of implementation. To address these challenges, future research should emphasize interdisciplinary collaboration, intelligent integration, and continuous innovation. A full-cycle technical system encompassing monitoring, repair, and evaluation must be standardized and demonstrated in practical applications. This will ultimately promote the transition of self-healing concrete technologies from laboratory-scale experiments to large-scale infrastructure applications.

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