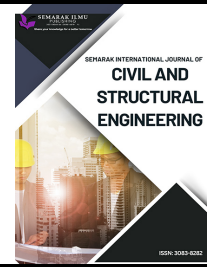




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Development of an IoT-Enabled Autonomous Crack Detection and Self-Sealing System for Concrete Structures

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ABSTRACT

Traditional concrete inspection methods are labour-intensive, time-consuming, and incapable of continuously monitoring hidden subsurface cracks. This study addresses the lack of an integrated, real-time autonomous repair system by developing an automated crack-detection and self-sealing prototype. The system integrates an HC-SR04 ultrasonic sensor for surface crack detection, an AMG8833 thermal sensor for internal defect identification, two Arduino Uno microcontrollers, an ESP32 module, a linear actuator, and a cement-spraying mechanism, managed remotely via the Blynk Internet of Things platform. Experimental testing of the laboratory prototype demonstrated that the ultrasonic sensor, positioned at a fixed distance of 3 cm, successfully detected surface cracks with measured peak depths of 1.8 cm and 1.2 cm, yielding an average depth of 1.5 cm. Under sunlight, the thermal sensor identified internal defects by recording temperature differences, with the crack area averaging 34.5°C compared to 30.3°C in the surrounding regions. The ESP32 module successfully transmitted real-time alerts to the Blynk application when temperature readings exceeded 28°C, and the linear actuator and spraying mechanism automatically sealed the detected cracks with cement. This work demonstrates the viability of combining intelligent sensing and automation to improve the maintenance efficiency of concrete infrastructure.

1. Introduction

Concrete represents one of the most widely utilised building materials globally, serving as the primary structural foundation for critical modern infrastructure such as buildings, bridges, roadways, tunnels, dams, and industrial facilities [1]. This widespread selection is primarily attributed to its high compressive resistance, long-term durability, adaptability, and economic feasibility. The strength, durability, and cost-effectiveness of concrete structures make them highly desirable and indispensable components of modern public and private infrastructure [2,3].

Despite these advantages, concrete structures are subject to progressive deterioration over their life cycles as a result of continuous mechanical loading, environmental exposure, thermal expansion,

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drying shrinkage, chemical reactions, and material ageing [4,5]. These combined factors inevitably compromise the overall structural integrity, giving rise to micro-cracks, surface cracks, and internal cracks that dramatically shorten the service life of the infrastructure. While surface-level cracks are easily detectable through conventional visual inspection, internal and micro-cracks remain concealed within the concrete material, rendering them extremely difficult to detect during their initial stages of formation [6]. If left unrepaired, these defects provide direct pathways for water, oxygen, and corrosive chemicals to seep into the concrete matrix, which initiates corrosion of the steel reinforcement, degrades the mechanical bond between the steel and concrete, and ultimately leads to a severe loss of the load-carrying capacity of the structure [7]. This progression results in undetected structural deterioration, high maintenance costs, and potentially catastrophic structural failures.

Traditional structural health monitoring has relied heavily on manual visual inspections and conventional non-destructive testing methods, such as ultrasonic pulse velocity and rebound hammer tests [8]. While these diagnostic methods are helpful for understanding concrete conditions, they are expensive, labour-intensive, time-consuming, and inherently incapable of providing continuous, real-time monitoring [9]. Furthermore, existing repair techniques, including cement grouting, epoxy injection, and polymer sealing, remain manual processes that are typically deployed only after significant cracking has become visible to the naked eye [10]. While computer vision and deep learning models have recently been developed for crack and defect detection with high accuracy, they require substantial computational resources, massive labelled training datasets, and highly controlled environmental conditions, which makes them unsuitable for low-cost, resource-constrained embedded systems [11,12].

Recent advancements in infrared thermography have enabled the non-destructive detection of concrete subsurface defects by analysing natural temperature distributions [13]. Similarly, convolutional neural networks have been applied to thermal images to automate damage classification in masonry and concrete structures [10]. However, these thermographic approaches remain purely diagnostic, offering no immediate, automated physical remediation once a defect is identified [13,14]. Additionally, while autonomous materials such as microcapsule-based self-healing concrete have been developed, their physical repair capacity is limited to micro-scale cracking, leaving larger macro-cracks unrepaired without manual mechanical intervention [15]. Although substantial research has been dedicated to the independent areas of defect visualisation and self-healing concrete materials, few studies have combined automated crack detection with a real-time, mechanical self-sealing mechanism in a single integrated prototype. The vast majority of current systems require manual intervention after detection and lack any real-time autonomous maintenance capability. Moreover, the integration of long-range IoT communication has been largely absent from automated concrete repair systems, which severely limits remote monitoring and prompt maintenance coordination.

To overcome these limitations, this research presents the design and development of an automated concrete crack detection and self-sealing system. The primary objective of this study is to construct an integrated, low-cost laboratory prototype that provides surface crack detection via an ultrasonic sensor, internal defect identification via an AMG8833 thermal sensor, an Arduino-based mechanical control unit, a linear actuator for horizontal movement, an automated cement-spraying mechanism for crack repair, and real-time remote notification capabilities via an ESP32 microcontroller and the Blynk IoT platform. The ultimate goal of this system is to make concrete inspection more efficient, minimise manual labour, and contribute to the advancement of smart, automated, and sustainable infrastructure maintenance.

2. Literature Review and Related Work

Structural health monitoring in civil engineering has historically transitioned from manual visual assessments to advanced sensor-based diagnostics to address the progressive deterioration of critical concrete infrastructure [16,17]. Traditional inspection is heavily dominated by manual visual examinations and conventional non-destructive testing, such as the ultrasonic pulse velocity test and rebound hammer test. While these non-destructive techniques are useful for understanding localised concrete conditions, they are expensive, labour-intensive, time-consuming, and fail to provide continuous, real-time monitoring of structural health [18]. Furthermore, while surface cracks are easily visible, internal and micro-scale cracks remain concealed within the concrete matrix and are difficult to detect in their early stages, permitting the infiltration of water and corrosive agents that degrade reinforcing steel and overall load-bearing capacity [19,20].

To automate this diagnosis, recent research has explored image processing and deep learning algorithms for visual surface crack detection [21]. Although deep learning models can achieve high classification and detection accuracies above 90 %, they require substantial computational resources, massive labelled training datasets, and highly controlled environmental conditions, which makes them unsuitable for low-cost, resource-constrained embedded systems [22].

To overcome the computational barriers of deep learning, conventional ultrasonic pulse velocity techniques calculate the transit-time of acoustic waves between transducers to estimate concrete crack depths [23]. While highly sensitive to structural discontinuities, traditional ultrasonic pulse velocity testing remains a static, manual procedure requiring precise, physical sensor placement across concrete surfaces, making continuous automated scanning impractical [24]. Concurrently, active and passive infrared thermography has emerged as a key tool for visualising concrete subsurface defects by capturing natural surface temperature differences caused by the lower thermal conductivity of air-filled internal delaminations [25,26]. Under natural sunlight, temperature gradients form between solid concrete and internal void areas, allowing advanced thermal cameras to isolate defect regions [27, 28]. However, industrial-grade thermography equipment remains highly expensive and computationally complex to interpret, limiting its application in localised, low-power embedded infrastructure [29]. Low-cost thermographic microbolometers, such as the 8×8 pixel AMG8833 sensor array, have shown potential for micro-scale thermal signature mapping, but their limited resolution requires extremely short scanning distances (under 45 cm) to resolve localised heat concentrations.

The proposed system addresses these diagnostic and cost limitations by integrating a dual-sensor scanning array consisting of a low-cost HC-SR04 ultrasonic sensor and an AMG8833 thermal array sensor on a single linear-actuated gantry. Rather than relying on expensive industrial thermography or computationally intensive deep learning algorithms, this laboratory prototype operates on simple microcontrollers at a close scanning distance of 3 cm. This design allows localised, non-destructive surface depth estimation and subsurface thermal profiling to be conducted in real time without high computational or equipment overhead.

Once a concrete defect is identified, conventional repair approaches rely on manual, reactive techniques such as cement grouting, epoxy injection, and polymer sealing [10,21]. These manual maintenance methods are typically executed only after significant macroscopic cracking is visible, during which substantial structural degradation may have already occurred [21]. To automate this process, researchers have investigated autonomous self-healing concrete incorporating materials such as superabsorbent polymers, intelligent CO₂-responsive polymers, and microcapsules containing healing agents [30-32]. While these advanced bio-chemical and polymer-based materials autonomously repair micro-cracks at early stages, they are physically constrained by their

microcapsule volumes and cannot remediate larger macro-cracks, which still require manual mechanical repairs [33].

To scale up automated maintenance to macro-cracks, engineering research has shifted toward automated mechanical repair systems, including modified three-dimensional printers and mobile robotic platforms designed to deposit repair agents directly into surface cracks [27,34]. Recent robotic prototypes, such as the CrackRepairBot, leverage computer-vision-guided nozzles to apply biological repair agents exclusively to narrow drying and shrinkage cracks, saving raw materials while mapping larger cracks for manual engineers [35]. Similarly, advanced multi-axis robotic arms utilise progressive path optimisation to adjust sealant deposition speeds based on local crack cross-sectional areas [36]. However, these robotic systems require extensive computational frameworks, large multi-axis manipulators, and high-performance edge single-board computers, which are costly and physically difficult to deploy inside narrow or low-clearance infrastructure spaces [24].

The proposed prototype addresses the limitations of both microscopic self-healing materials and heavy, high-cost robotic arms. By combining a physical linear actuator with a localised cement-spraying nozzle directly controlled by the dual-sensor unit, the prototype achieves immediate, automated mechanical repair of macro-cracks. This low-cost, closed-loop gantry system executes targeted cement spraying immediately upon crack detection, bridging the gap between passive chemical self-healing and complex, expensive multi-axis robotic manipulators.

Recent advancements in microcontrollers and long-range wireless communication have enabled the deployment of intelligent structural health monitoring systems [37]. Wireless sensor networks utilising low-power, long-range connection technologies allow continuous, remote transmission of environmental and structural data to centralised databases [38]. However, most traditional Internet of Things (IoT) monitoring systems remain purely diagnostic, focusing exclusively on data logging and cloud visualisation without any physical, real-time maintenance feedback loop. For instance, smart-city testbeds and large-scale public monitoring networks transmit strain, temperature, and acceleration data to remote servers, but they still require manual maintenance crews to inspect and repair the reported defects.

Modern civil engineering structural health monitoring systems increasingly deploy Internet of Things nodes utilising ESP32 or ESP8266 microcontrollers to stream raw physical data, such as acoustic emissions, vibration frequencies, and internal moisture levels, to cloud platforms like Blynk or custom web servers [38]. These frameworks allow engineers to monitor environmental conditions from any location, improving predictive maintenance modelling. However, because these systems lack localised actuation, the transmission of warning alerts does not result in immediate physical remediation, leading to ongoing crack propagation while awaiting human intervention [39].

The proposed system addresses the absence of a closed-loop IoT repair process by combining real-time remote notification with localised, autonomous physical actuation. Utilising an ESP32 microcontroller and the Blynk Internet of Things platform, the system establishes a low-power, two-way loop. The ESP32 transmits immediate, real-time alert notifications to the user's mobile device when the thermal sensor detects concrete temperature values exceeding the 28°C threshold or when the ultrasonic sensor detects surface depth anomalies. Concurrently, the local controller network operates an Arduino-driven linear actuator and cement-spraying nozzle to immediately seal the crack, ensuring physical remediation is executed simultaneously with remote cloud notification.

3. Methodology

3.1 Systems Development Life Cycle (SDLC) Framework

The development of the autonomous concrete crack detection and self-sealing system was executed through a structured System Development Life Cycle framework, which comprised five sequential phases: planning, analysis, design, testing, and implementation.

1. Planning Phase: In this initial stage, the operational limitations of traditional concrete inspection and repair methodologies were identified. A literature survey revealed that conventional visual examinations and manual non-destructive testing techniques are labour-intensive, time-consuming, and incapable of continuously monitoring subsurface defects. To address these deficiencies, three specific operational goals were established for the proposed prototype: the automated detection of surface and internal concrete cracks, the physical execution of a cement-based self-sealing routine, and the continuous transmission of real-time monitoring notifications.

2. Analysis Phase: In the second phase, various diagnostic sensing methodologies — specifically computer-vision-based image processing, ultrasonic waves, and thermal infrared sensing — were analysed and compared. High-performance image processing was excluded due to its high cost and high demand for computational resources, making it unfeasible for a low-cost embedded system. Consequently, an HC-SR04 ultrasonic sensor was selected to provide a simple, economical, and non-destructive method for surface crack depth estimation. Additionally, an AMG8833 thermal sensor was chosen to identify subsurface cracks by measuring heat accumulation within the concrete defects. Dual Arduino Uno microcontrollers and an ESP32 microcontroller module were selected as the processing and communication core due to their compatibility, programmability, and suitability for Internet of Things integration.

3. System Design Phase: In the third phase, the physical, electronic, and software properties of the system were integrated into a unified gantry mechanism. This included designing the linear-actuator framework, selecting motor driver circuits, configuring microcontroller pins, and writing software routines to coordinate sensor readings, motorised motion, and cement spraying.

4. Testing Phase: In the fourth phase, individual subsystem testing was performed to evaluate the performance of the sensors, the linear-actuator control, and the Internet of Things messaging. The HC-SR04 ultrasonic sensor was calibrated for surface scanning at a fixed distance of 3 cm. The thermal sensor was tested under natural sunlight to characterise concrete surface temperature gradients, and the ESP32 module was configured to transmit data packets to the Blynk cloud server.

5. Implementation Phase: In the final phase, the individual mechanical, electronic, and software components were integrated into a single laboratory prototype. Closed-loop tests were conducted on concrete specimens to verify that the linear actuator could position the sensing gantry, that the dual-sensor array could scan for surface and internal cracks, and that the cement-spraying nozzle could execute immediate repair while simultaneously sending remote mobile notifications.

3.2 Hardware and Mechanical Prototype Design

The physical laboratory prototype was constructed as a mechanised, one-dimensional linear scanning gantry designed to move across concrete surfaces. The mechanical structure of the prototype consisted of a linear actuator configured to translate the sensor scanning module horizontally along a predetermined scan line. The scanning module housed the HC-SR04 ultrasonic sensor and the AMG8833 thermal sensor. The ultrasonic sensor was positioned downward-facing to continuously measure the distance to the concrete surface, while the AMG8833 infrared thermal sensor was positioned adjacent to it to record temperature profiles of the concrete.

For physical crack repair, a cement-spraying nozzle mechanism was mounted directly on the translating carriage. Upon receiving a trigger signal from the electronic control unit, the spraying mechanism automatically dispensed a cementitious slurry into the detected crack opening. A computer-aided design (CAD) rendering of the scanning and spraying gantry is shown in Figure 1.

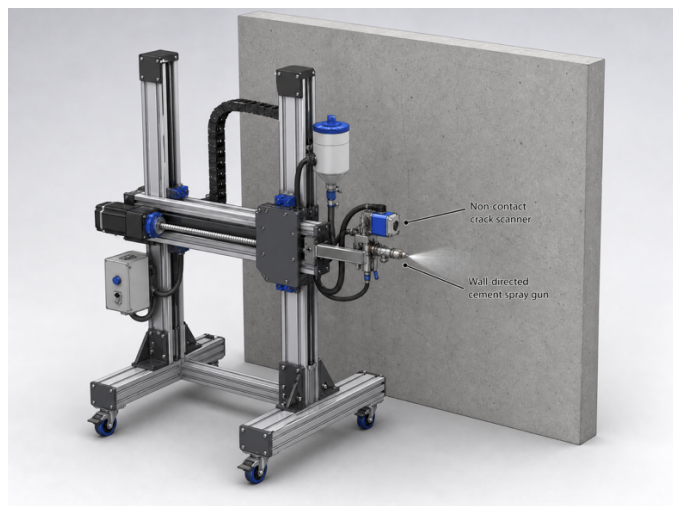


Fig. 1. CAD model of the linear-actuated crack-scanning and cement-spraying gantry

3.3 Electronic Control and Microcontroller Architecture

The electronic control architecture was designed as a distributed processing network, utilising two Arduino Uno microcontrollers and one ESP32 module to manage distinct hardware subsystems.

1. Motion Control Subsystem: A dedicated Arduino Uno microcontroller was programmed to govern the horizontal translation of the linear actuator. This microcontroller was interfaced with an L298N dual H-bridge motor driver, which regulated the voltage and current supplied to the linear actuator's motor, enabling smooth forward and reverse movement across the concrete surface.

2. Sensing and Actuation Subsystem: A second, independent Arduino Uno microcontroller was used to process ultrasonic signal data and actuate the repair mechanism. This microcontroller continuously read the trigger and echo pins of the HC-SR04 ultrasonic sensor, calculated the distance to the concrete surface, and generated the digital control signals used to operate the cement-spraying mechanism.

3. Thermal Sensing and IoT Communication Subsystem: An ESP32 microcontroller was deployed to manage thermal data acquisition and wireless network transmission. The ESP32 was connected to the AMG8833 thermal sensor via an Inter-Integrated Circuit (I2C) serial interface and used its built-in Wi-Fi module to connect to the local network, enabling continuous, real-time wireless communication with the Blynk IoT cloud server.

The integration of these separate processing nodes allowed for concurrent sensor scanning, mechanical translation, physical sealing, and wireless alerts, minimising the processing delays that could arise from a single microcontroller execution thread. The circuit diagram of the electronic control system is shown in Figure 2.

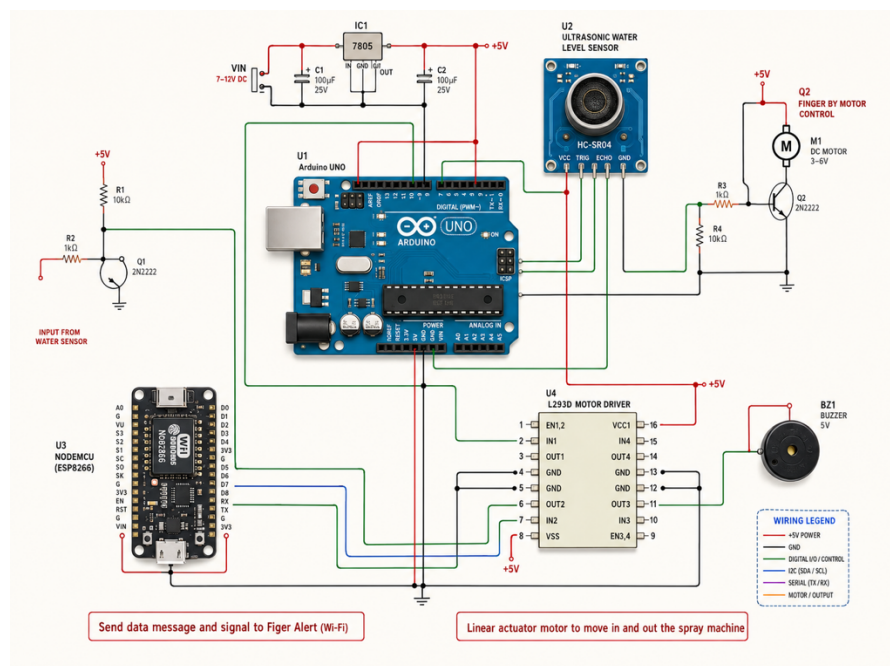


Fig. 2. Circuit diagram of the electronic control system, showing the Arduino Uno, ESP32 (NodeMCU), AMG8833 thermal module, and L298N motor driver

3.4 Experimental Test Setup and Scanning Procedures

Experimental testing was conducted under laboratory conditions to validate the performance of the prototype. Concrete test specimens were prepared with artificial surface and internal cracks.

The laboratory testing procedure was conducted in the following sequence:

1. Subsystem Verification: Prior to full system integration, individual components were tested. The HC-SR04 ultrasonic sensor was placed at a fixed scanning distance of 3 cm from the concrete surface, defined as the vertical clearance between the transmitter face and the flat, undamaged surface of the concrete block.

2. Thermal Characterisation: To test the subsurface detection capability of the AMG8833 thermal sensor, the concrete specimens were exposed to natural sunlight. This exposure was required to establish a passive thermal gradient across the concrete surface, where the lower thermal conductivity of air-filled internal defects compared to solid concrete would result in localised heat accumulation.

3. Wireless Notification Setup: The ESP32 module was programmed with the local Wi-Fi credentials and the Blynk authentication token. A mobile smartphone running the Blynk application was linked to the ESP32 via a virtual dashboard configured to display real-time concrete temperature readings.

4. Integrated Closed-Loop Testing: The concrete specimen was aligned beneath the scanning gantry. The linear actuator was activated to move the dual-sensor scanning module horizontally at a constant velocity. The ultrasonic sensor continuously measured the surface profile; if the calculated depth deviated from the calibrated baseline of 3 cm, a surface crack was registered. Concurrently, the AMG8833 thermal sensor recorded the thermal distribution; if the measured temperature exceeded a critical threshold of 28°C, an internal defect was registered.

5. Repair and Notification Execution: Upon detection of a crack, the local controller network automatically triggered the cement-spraying mechanism to deposit cement slurry into the defect

area. Simultaneously, the ESP32 transmitted a real-time push alert to the user's Blynk mobile interface, indicating that structural damage had been identified and repaired.

3.5 Analytical and Data Processing Methods

The data processing routines utilised simple, low-cost analytical calculations to detect structural defects and trigger repair actions.

1. **Surface Crack Depth Estimation:** The ultrasonic sensor calculated the distance to the concrete surface by transmitting a 40 kHz acoustic pulse and measuring its time of flight. This acoustic measurement approach follows the general principles for indirect ultrasonic surface scanning outlined in BS 1881-203 [40, 41] and ASTM C597 [42]. The distance from the sensor to the target was calculated using the sound-wave propagation velocity in air, approximately 343 m/s at room temperature. The baseline distance to the undamaged concrete surface was calibrated at exactly 3 cm. When the sensor carriage passed over a surface crack, the acoustic wave travelled a longer path to the bottom of the crack, resulting in an increased round-trip transit time and a greater calculated distance. The depth of the crack was computed using the following formula:

$$\text{Depth} = \text{Measured Distance} - \text{Baseline Distance (3 cm)} \quad (1)$$

Two peak distance readings were recorded during the experimental scans: 4.8 cm and 4.2 cm. Applying Eq. (1):

$$\text{Depth}_1 = 4.8 \text{ cm} - 3.0 \text{ cm} = 1.8 \text{ cm}$$

$$\text{Depth}_2 = 4.2 \text{ cm} - 3.0 \text{ cm} = 1.2 \text{ cm}$$

The average crack depth was calculated as 1.5 cm. The differences between the individual distance measurements were attributed to acoustic wave scattering and wave diffraction occurring at the rough edges of the concrete crack opening.

2. **Thermal Profile Interpretation:** Subsurface defect identification was achieved by capturing the temperature differences across the concrete surface using the AMG8833 infrared sensor array, an uncooled microbolometer sensor containing an 8×8 thermopile array that measures infrared radiation in the 8–14 μm wavelength range [28]. Under passive solar heating, thermal energy accumulated in the concrete. Because air-filled subsurface cavities have a lower thermal conductivity than solid concrete, heat transfer was restricted, resulting in a localised temperature rise directly above the defect area. The sensor array recorded an average temperature of 34.5°C in the crack region, compared with an average of approximately 30.3°C in the surrounding healthy concrete regions.

3. **Threshold Action Logic:** The ESP32 was programmed with a threshold comparison loop. The system continuously evaluated the maximum temperature read by the AMG8833 array. If the temperature value exceeded 28°C, the system registered an active defect state, which triggered the immediate transmission of real-time wireless packets to the Blynk mobile application. Simultaneously, the Arduino microcontroller initiated the horizontal positioning and cement-spraying sequence to seal the physical opening.

4. Results

4.1 Ultrasonic Surface Crack Detection and Depth Measurement

To evaluate the surface defect scanning performance of the laboratory prototype, concrete specimens were positioned at a fixed vertical distance of 3.0 cm from the HC-SR04 ultrasonic sensor. During the automated horizontal scanning sweep, the sensor successfully identified surface-opening cracks by measuring the transit-time changes of the reflected acoustic waves. The experimental run

recorded two distinct peak distance readings, as shown in Figure 3. When calibrated against the baseline surface clearance, these raw telemetry readings corresponded to individual surface crack depths of 1.8 cm and 1.2 cm respectively, resulting in a calculated average crack depth of 1.5 cm, as summarised in Table 1. The minor discrepancy of 0.6 cm between the two peak readings was attributed to the physical phenomena of wave scattering and wave diffraction occurring during acoustic wave transmission across the irregular concrete boundaries.

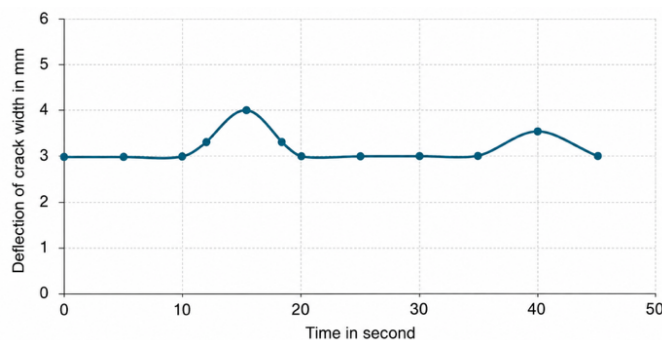


Fig. 3. Ultrasonic distance signal recorded during the crack-detection scan

Table 1

Summary of ultrasonic crack-depth measurements

Peak reading	Measured distance (cm)	Calculated crack depth (cm)
1	4.8	1.8
2	4.2	1.2
Average	–	1.5

4.2 Subsurface Thermal Profiling and Defect Mapping

The subsurface crack and void detection capability of the integrated AMG8833 thermal sensor was evaluated by subjecting the concrete specimens to natural solar radiation. This experimental setup allowed the system to exploit the passive temperature variations that develop between solid and compromised concrete regions over a diurnal cycle. The thermal sensor successfully resolved clear temperature gradients across the concrete surface, as shown in Figure 4. The damaged crack region exhibited an average temperature of 34.5°C, whereas the surrounding solid concrete regions maintained a lower average temperature of approximately 30.3°C. This temperature differential of 4.2°C confirms that the air-filled crack boundaries acted as local thermal barriers, leading to localised heat accumulation in the damaged area.

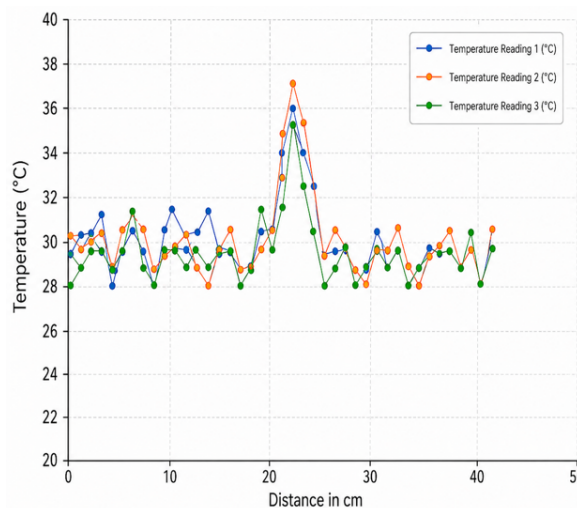


Fig. 4. Surface temperature record across the concrete block, showing the localised temperature rise at the crack region

4.3 Internet of Things Notification and Remote Monitoring

The remote connectivity and alert system were tested using the integrated ESP32 microcontroller linked to the Blynk mobile application. The control algorithm was programmed with a static thermal trigger threshold of 28.0°C. During experimental testing, when the AMG8833 thermal sensor recorded concrete surface temperatures exceeding this limit, the ESP32 successfully transmitted real-time status data and crack warnings to the Blynk mobile dashboard, as shown in Figure 5. This verification confirms that the prototype provides reliable, continuous remote structural health monitoring under active thermal conditions.

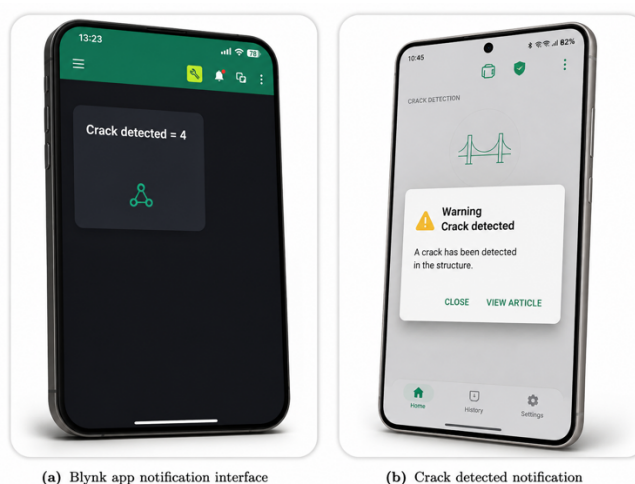


Fig. 5. (a) Blynk application notification interface and (b) crack-detected alert received on a mobile device

4.4 Integrated Autonomous Motion and Cement-Sealing Execution

To evaluate the closed-loop performance of the fully integrated prototype, a complete diagnostic and maintenance cycle was executed. During this test, all subsystems — including horizontal scanning motion, dual-sensor data acquisition, automated cement spraying, and cloud communication — were operated simultaneously on a single control platform, as previously illustrated in Figures 1 and

2. The linear gantry actuator successfully translated the sensor housing, providing smooth horizontal motion across the concrete surface. Upon simultaneous detection of surface depth anomalies by the ultrasonic sensor and elevated temperatures by the thermal sensor, the microcontroller network initiated a dual response: the L298N driver and relay system automatically triggered the cement-spraying nozzle to deposit repair material directly into the identified crack channel, while the ESP32 module concurrently transmitted an alert notification to the remote user via the Blynk application. The successful execution of this joint routine confirms the baseline functional viability of the closed-loop autonomous maintenance prototype.

5. Discussion

5.1 Interpretation of Key Findings and Objectives

The primary objective of this study was to design, construct, and evaluate an integrated, low-cost autonomous prototype for concrete crack detection and mechanical self-sealing using a dual-sensor array and an Internet of Things (IoT) interface. The experimental evaluation of the developed prototype validated this concept by demonstrating successful automated linear scanning, surface crack profiling, subsurface thermal anomaly detection, and closed-loop cement deposition.

The ultrasonic sensor system, operated at a close scanning clearance of 3 cm, successfully detected open surface cracks, registering raw distance peaks of 4.8 cm and 4.2 cm. These peak readings mathematically correspond to localised crack depths of 1.8 cm and 1.2 cm respectively, establishing a calculated average surface crack depth of 1.5 cm. This finding is significant as it demonstrates that non-contact, low-cost ultrasonic components can be mechanically automated to perform localised depth profiling without requiring acoustic coupling gels or manual probe placement.

Simultaneously, the thermal sensing subsystem successfully identified subsurface anomalies by mapping surface temperature distributions under natural solar radiation. The concrete crack zone exhibited an average temperature of 34.5°C, while the surrounding solid regions remained at approximately 30.3°C, revealing a distinct thermal gradient of 4.2°C. This temperature differential was sufficient to trigger real-time remote telemetry transmission via the ESP32 module to the Blynk cloud platform when temperatures exceeded the pre-configured 28°C threshold. Once a crack was identified by either sensor subsystem, the microcontroller network coordinated the mechanical linear actuator and cement-spraying nozzle to execute targeted physical remediation. This closed-loop integration of real-time monitoring and physical repair satisfies the fundamental goal of minimising manual inspection labour and advancing automated infrastructure maintenance.

5.2 Contextualisation within Existing Literature

First, the thermal sensing results directly align with the passive thermographic principles described by Gu et al. [13], who demonstrated that natural solar heating generates detectable thermal signatures over concrete subsurface defects due to the lower thermal conductivity of air-filled internal delaminations. The 4.2°C thermal gradient observed in this study confirms this phenomenon, indicating that even localised macro-cracks accumulate solar heat. However, while traditional thermography relies on expensive, industrial-grade infrared cameras as documented by Pozzer et al. [43], this study extends the field by showing that low-cost microbolometers, specifically the 8×8 pixel AMG8833 sensor array, can successfully isolate these temperature boundaries when positioned at a highly localised scanning distance of 3 cm.

Second, this research addresses a functional gap in computer-vision-based structural diagnostics. Although advanced convolutional neural networks and deep learning models achieve high crack classification accuracies on heritage masonry and concrete surfaces, as shown by Seo et al. [14], they remain purely diagnostic and require substantial computational edge-processing hardware. The prototype developed in this work extends these diagnostic approaches by directly linking low-power microcontroller detection to physical linear actuation and cement deposition, providing an immediate, real-time maintenance feedback loop that does not require heavy computational resources.

Third, the physical repair capability of the automated spraying nozzle addresses the volume constraints inherent in autonomous self-healing materials. As documented by Singh and Tarannum [44], bio-chemical and microcapsule-based self-healing concrete is restricted by microcapsule volumes, limiting self-repair to early-stage microscopic cracking. The automated mechanical prototype developed in this study bridges this gap by demonstrating the capacity to physically deposit cementitious sealant into larger macroscopic cracks of up to 1.8 cm in depth, which would otherwise require intensive manual repair.

Fourth, the non-contact, automated ultrasonic scanning method used in this study contrasts with traditional, manual ultrasonic pulse velocity (UPV) techniques. Standard concrete depth measurements, such as those governed by ASTM C597 and BS 1881-203, utilise direct or indirect transducer arrangements that require couplant gels, smooth surface preparation, and precise manual positioning to capture acoustic transit-times [45]. In contrast, the automated linear scanning gantry presented here eliminates operator subjectivity and surface couplant requirements by moving a low-cost, non-contact ultrasonic sensor at a fixed vertical clearance of 3 cm. While manual UPV testing remains more accurate for deep, internal cracking [46], this automated prototype provides a more rapid, repeatable, and cost-effective screening tool for open surface-breaking cracks.

Finally, the mechanical design of this prototype offers a simplified, low-cost alternative to complex robotic maintenance systems. Recent robotic repair systems, such as the vision-guided CrackRepairBot [35] and multi-axis adaptive robotic arms [47], utilise multi-degree-of-freedom manipulators to trace and seal pavement and structural cracks. Although these advanced robotic systems offer high spatial resolution, they are expensive and difficult to deploy in tight, low-clearance structural spaces. The single-axis linear-actuated gantry developed in this work provides a lightweight, economical alternative that successfully coordinates sensor scanning and sealing within a single, highly integrated low-power microcontroller network.

5.3 Physical Mechanisms Underlying Experimental Observations

The ultrasonic sensor recorded localised distance peaks of 4.8 cm and 4.2 cm when passing over the surface cracks. As the high-frequency acoustic wave emitted by the HC-SR04 transmitter reaches the boundary of an open concrete crack, the sound waves do not reflect off a uniform plane; instead, the sudden geometry change causes the acoustic energy to scatter and diffract around the sharp edges of the crack opening. This scattering increases the travel time of the reflected echo back to the receiver transducer, which the microcontroller interprets as an increased distance (the peak readings), thereby mapping the spatial profile and localised depth of the crack.

The thermal sensor recorded an average crack temperature of 34.5°C compared with 30.3°C in the surrounding solid regions. Under passive solar loading, concrete absorbs solar radiation and transfers heat downward via conduction. An open or subsurface crack, however, contains air, which has a significantly lower thermal conductivity than solid concrete. This air barrier acts as an insulator, disrupting downward heat dissipation, so thermal energy accumulates in the concrete material

directly above and adjacent to the crack, producing localised surface hot spots that are readily detected by the microbolometer array.

5.4 Limitations of the Current Study

While the laboratory prototype successfully validated the dual-sensor automated repair concept, several structural and operational limitations must be acknowledged:

1. **Spatial Scanning Constraint:** The mechanical prototype utilises a single-axis linear actuator, which limits scanning to a one-dimensional linear path. As a result, the system is currently incapable of tracking or sealing complex, multi-directional, or diagonal cracking patterns.

2. **Concrete Specimen Variables:** The experimental testing was conducted on a limited set of laboratory concrete specimens. The study did not evaluate how variations in concrete age, moisture content, surface roughness, aggregate size, or the presence of steel reinforcement would affect the accuracy of the ultrasonic distance measurements or the thermal profiles.

3. **Environmental Dependence:** The subsurface defect detection system relies on natural solar radiation (sunlight) to generate the required thermal gradients. This limits the reliability of the thermal sensor in shaded, indoor, underground, or night-time environments where passive thermal gradients are absent.

4. **Spraying Mechanism Precision:** The current mechanical cement-spraying nozzle operates as a basic open-loop system. The prototype lacks precise flow-rate control and feedback-driven positioning, which can lead to material overspray, uneven sealant thickness, or incomplete filling of deeper crack geometries.

6. Conclusions

This study successfully designed and evaluated an automated crack detection and self-sealing system for concrete structures, demonstrating the viability of integrating low-cost sensing with real-time maintenance automation. Experimental testing of the laboratory prototype confirmed that the non-contact HC-SR04 ultrasonic sensor successfully profiled open surface cracks, measuring an average depth of 1.5 cm at a 3 cm scanning distance, while the AMG8833 thermal sensor identified subsurface anomalies by mapping localised temperature differences under natural sunlight. By linking these dual-sensor diagnostics to an Arduino-controlled linear actuator and a cement-spraying mechanism, the prototype executed immediate physical repairs while simultaneously transmitting remote alerts to users via the ESP32 module and the Blynk Internet of Things platform. This closed-loop configuration provides an efficient, low-power maintenance solution that reduces manual labour requirements and inspection time. Future work will focus on optimising the flow-rate precision of the cement-spraying process, incorporating image-processing algorithms to enhance diagnostic accuracy, and developing an X-Y axis scanning gantry to trace and repair multi-directional cracking patterns on larger, real-world concrete surfaces.

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