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Digital Twin Based Smart Monitoring of RCC Structural Elements Using IoT

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ABSTRACT: This study presents the development and implementation of a low-cost, Internet of Things (IoT)-based system for monitoring the corrosion behaviour of reinforced concrete structures in near real-world conditions. The system integrates an Ag/AgCl reference electrode for half-cell potential (HCP) measurement with an ESP32-based data acquisition unit, enabling continuous sensing, real-time data processing, and wireless transmission to a remote interface. The hardware architecture is designed for ease of deployment on existing structural elements, with a focus on stability, scalability, and long-term monitoring capability. The experimental setup involves instrumenting a reinforced concrete specimen with embedded sensing components and deploying the system under chloride exposure conditions representative of field environments. While accelerated corrosion techniques are employed to obtain measurable responses within a practical timeframe, the primary focus is on validating the performance, reliability, and responsiveness of the monitoring device. The system successfully captures temporal variations in corrosion potential, allowing for assessment of corrosion probability and intensity. The results demonstrate that the proposed device can function as a practical structural health monitoring tool, offering continuous, low-cost, and remotely accessible insights into reinforcement condition. This work establishes a foundation for real-life deployment on civil infrastructure and supports future integration with predictive analytics and digital twin frameworks for proactive maintenance and decision-making.

1. INTRODUCTION

Reinforced Cement Concrete (RCC) is the most widely used construction material due to its strength, durability, and versatility. However, its long-term performance depends greatly on the protection of embedded steel reinforcement from corrosion. Corrosion of reinforcement is one of the major causes of deterioration in concrete structures and leads to cracking, spalling, delamination, and eventual structural failure. The damage caused by reinforcement corrosion significantly increases maintenance costs and reduces the service life of civil infrastructure.

Traditional inspection and monitoring methods such as visual inspection, half-cell potential measurements, and laboratory testing are often time-consuming, labour intensive, expensive and reactive in nature. These methods typically identify damage only after it becomes visible, which limits their usefulness in preventive maintenance. The recent advancement of digital technologies such as the Internet of Things (IoT) and Digital Twin (DT) frameworks has enabled continuous, real-time, and data-driven monitoring of structures.

Digital Twin technology allows the creation of a virtual representation of a physical structure that continuously receives live data from sensors embedded in the field. By combining Digital Twin models with IoT-based sensors, it becomes possible to detect and visualize reinforcement corrosion before major deterioration occurs. Such integration enables real-time data acquisition, processing, and intelligent decision-making, contributing to improved safety, durability, and cost efficiency of concrete structures.

1.2 SMART MONITORING OF RCC STRUCTURES

Smart monitoring involves the use of advanced sensing technologies and communication systems to assess the health and performance of RCC structures. Embedded and surface mounted sensors can monitor environmental and electrochemical parameters such as temperature, humidity, and chloride ion concentration, which directly affect the corrosion rate of reinforcement. These sensors transmit data to a centralized system through wireless networks, enabling remote and continuous assessment.

IoT-based smart monitoring systems reduce the dependency on manual inspection and allow early identification of deterioration patterns. When integrated with a Digital Twin environment, the sensor data can be visualized and analysed to simulate the behaviour of the structure in real time. This ensures continuous observation of structural performance and supports data-driven maintenance planning.

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1.3 DIGITAL TWIN TECHNOLOGY

A Digital Twin is a virtual model that replicates the characteristics, behaviour, and condition of a physical asset using real-time data. In civil engineering, Digital Twins are developed by integrating structural models, sensor data, and simulation algorithms to represent the actual state of infrastructure systems. The virtual model updates continuously as the physical structure changes, allowing accurate visualization and performance assessment.

In the context of corrosion monitoring, a Digital Twin can simulate the initiation and progression of reinforcement corrosion by processing data obtained from sensors embedded in the concrete. This provides insights into the deterioration rate, expected service life, and necessary maintenance actions. The dynamic nature of the Digital Twin ensures that structural health information remains current, supporting predictive decision making and life-cycle management.

1.4 INTERNET OF THINGS (IoT) IN CIVIL INFRASTRUCTURE

The Internet of Things (IoT) facilitates interconnection between sensing devices and computational platforms through wireless communication technologies. IoT systems enable distributed sensing and remote data collection, making them suitable for large scale structural health monitoring applications.

For corrosion detection in RCC structures, IoT sensors are deployed to measure environmental and material parameters such as temperature, humidity, and chloride concentration. Data collected from these sensors are transmitted to a central server or cloud storage for analysis and visualization. Studies have shown that IoT-based frameworks can significantly improve the reliability and continuity of monitoring, enabling efficient maintenance planning and reduced operational costs.

1.5 INTEGRATION OF DIGITAL TWIN AND IoT

Integration of Digital Twin and Internet of Things (IoT) provides a comprehensive framework for real-time monitoring and maintenance of RCC structures. IoT sensors act as the data acquisition layer, while the Digital Twin functions as the visualization and simulation environment. Together, these technologies create a closed-loop system capable of detecting early signs of corrosion and monitoring deterioration trends.

In this integrated system, sensors embedded within the concrete continuously measure key environmental and material parameters such as temperature, humidity, and chloride concentration. These data are transmitted through wireless communication networks to a centralized cloud platform, where they are stored and processed.

The Digital Twin model receives this real-time data and updates the virtual representation of the physical structure accordingly. This enables engineers to visualize the current condition of the structure, track changes over time, and assess the progression of corrosion. The synchronization between the physical structure and its digital counterpart ensures that the model accurately reflects real-world conditions.

Such an approach enables continuous data exchange between the physical and digital systems, improving the efficiency of structural health monitoring. It supports informed decision-making for maintenance planning by providing timely insights into structural performance and deterioration patterns.

2. METHODOLOGY

2.1 EXPERIMENTAL WORKING OF DIGITAL TWIN–BASED MONITORING SYSTEM

The proposed methodology presents a systematic framework for monitoring reinforcement corrosion in RCC structures using IoT and Digital Twin technology. The system consists of two primary components: an IoT-based data acquisition system and a Digital Twin visualization model. Initially, sensors are installed on or within the concrete specimen to measure key environmental and electrochemical parameters, namely temperature, ambient humidity, and half-cell potential. These parameters are selected due to their direct relationship with corrosion activity.

The sensor nodes are connected to a microcontroller unit, which collects and transmits data to a cloud-based platform through wireless communication. The data transmission occurs at regular intervals, ensuring continuous monitoring of the structure under

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varying environmental conditions. A stable communication network is maintained using a Wi-Fi-enabled ESP32 , allowing real-time data transfer without manual intervention.

A Digital Twin model of the RCC element is developed using a 3D modelling platform. This virtual model is linked to the cloud database, enabling it to receive real-time sensor data. The Digital Twin updates dynamically to reflect the current condition of the structure, allowing visualization of environmental changes and corrosion-related indicators. This integration establishes a continuous feedback loop between the physical structure and its digital representation, supporting effective monitoring and assessment.

2.7 PARAMETER SELECTION

In the proposed corrosion monitoring framework, the selection of parameters is based on their direct influence on the electrochemical behaviour of reinforcement in reinforced concrete structures. Corrosion of steel reinforcement is governed by environmental exposure and electrochemical potential differences within the concrete. Therefore, the parameters chosen for this study are temperature, ambient humidity, and half-cell potential, as they provide a reliable indication of corrosion activity and surrounding environmental conditions.

Temperature and ambient humidity are critical environmental parameters that significantly influence the rate of corrosion. An increase in temperature accelerates electrochemical reactions and enhances ionic mobility within the concrete pore solution, thereby increasing corrosion rates. Similarly, higher ambient humidity contributes to the availability of moisture within the concrete, which is essential for the flow of ions and the continuation of corrosion processes. These parameters help in understanding the external exposure conditions that affect the durability of RCC structures.

Half-cell potential is the primary electrochemical parameter used to assess the probability of corrosion in embedded reinforcement. It provides a direct measurement of the electrical potential difference between the steel reinforcement and a reference electrode, indicating the likelihood of active corrosion. More negative potential values correspond to a higher probability of corrosion activity. By continuously monitoring half-cell potential along with temperature and humidity, a comprehensive assessment of both environmental influence and corrosion state can be achieved. These parameters are measured using appropriate sensors and transmitted through the IoT system to update the Digital Twin model for real-time visualization of structural condition

2.3 MODEL DETAILS

The monitoring system is composed of an IoT-based sensing unit and a Digital Twin model. The IoT unit consists of temperature and humidity sensors along with a half-cell potential measurement setup connected to an ESP32. This sensor is used to enable real-time monitoring in concrete specimens.

The Digital Twin model is developed using 3D modelling software Autodesk Revit. The model includes representation of the structural element along with the location of reinforcements. The virtual model is linked to the cloud database, allowing it to receive and display real-time sensor inputs.

The system ensures that any change in environmental conditions or corrosion potential is reflected in the Digital Twin, enabling accurate visualization of the structural condition over time.

2.4 IoT HARDWARE AND DATA ACQUISITION

The hardware setup includes sensors, a microcontroller unit, and wireless communication modules. Ambient temperature and humidity is measured using DHT11 sensor. Half-cell potential is measured using a standard reference electrode (such as Ag/AgCl electrode) connected to the reinforcement.

The sensor is interfaced with the ESP32, which performs analogue-to-digital conversion and transmits the data to a cloud platform via Wi-Fi. A local network or router ensures uninterrupted communication between sensor nodes and the cloud server.

The data acquisition system stores real-time readings and maintains a continuous record of parameter variations. Calibration of sensors is carried out prior to experimentation to ensure measurement accuracy and consistency.

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2.5 DATA PROCESSING AND INTERPRETATION

The collected sensor data are pre-processed to remove noise and ensure consistency. This includes filtering of irregular readings, handling missing values, and organizing the data into a structured format suitable for analysis.

Half-cell potential readings are interpreted based on established standards to determine the probability of corrosion activity. Temperature and humidity data are correlated with the observed potential values to understand environmental influence on corrosion behaviour.

The processed data are then transmitted to the Digital Twin platform, where they are used to represent the condition of the structure in a simplified and interpretable manner.

2.6 DIGITAL TWIN INTEGRATION AND VISUALIZATION

The Digital Twin serves as a virtual representation of the physical structure, updated using real-time sensor data. The cloud platform acts as an intermediary, receiving data from IoT devices and transmitting it to the Digital Twin environment.

The visualization module displays the condition of the structure using graphical representations such as color-coded indicators for corrosion intensity. Changes in temperature, humidity, and half-cell potential are reflected dynamically in the model, allowing users to monitor trends over time.

This integration enables engineers to remotely assess structural health, identify areas of concern, and make informed maintenance decisions without direct physical inspection.

2.7 VALIDATION AND PERFORMANCE EVALUATION

The proposed system is validated through experimental testing on reinforced concrete specimens equipped with sensors. Half-cell potential measurements obtained from the system are compared with standard reference readings to verify accuracy.

Temperature and humidity readings are also cross-checked with calibrated instruments to ensure reliability. The consistency and responsiveness of the Digital Twin model are evaluated based on its ability to accurately reflect real-time changes in the physical structure.

Performance evaluation focuses on data accuracy, system reliability, and effectiveness in detecting corrosion-prone conditions. The results confirm the feasibility of using an IoT-enabled Digital Twin system for real-time corrosion monitoring in RCC structures.

3. WORKING

3.1 PROTOTYPE

The developed prototype is designed to monitor environmental conditions and corrosion activity in reinforced concrete using an IoT-based system integrated with a Digital Twin framework. The system consists of an ESP32 microcontroller, a DHT11 temperature and humidity sensor, and an Ag/AgCl standard reference electrode for half-cell potential measurement. These components work together to collect real-time data and transmit it wirelessly for remote monitoring.

The DHT11 sensor is used to measure ambient temperature and relative humidity surrounding the concrete structure. These environmental parameters play a significant role in influencing corrosion rates. Simultaneously, the Ag/AgCl reference electrode is used to measure the half-cell potential of the embedded steel reinforcement. The electrode is placed in contact with the concrete surface, and the potential difference between the reinforcement and the reference electrode is measured through the ESP32. This potential value provides an indication of the likelihood of corrosion activity within the structure.

The ESP32 serves as the central processing and communication unit of the prototype. It collects analogue and digital signals from the sensors, processes the data, and converts it into readable values. Utilizing its built-in Wi-Fi capability, the ESP32

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transmits the collected data to a mobile application in real time. The mobile application acts as a user interface, displaying temperature, humidity, and half-cell potential values in an organized manner.

This system enables continuous monitoring without the need for manual inspection. By observing the variation in half-cell potential along with environmental conditions, the user can assess the corrosion state of the reinforcement. The integration of sensing, processing, and wireless communication makes the prototype a compact and efficient solution for real-time structural health monitoring.

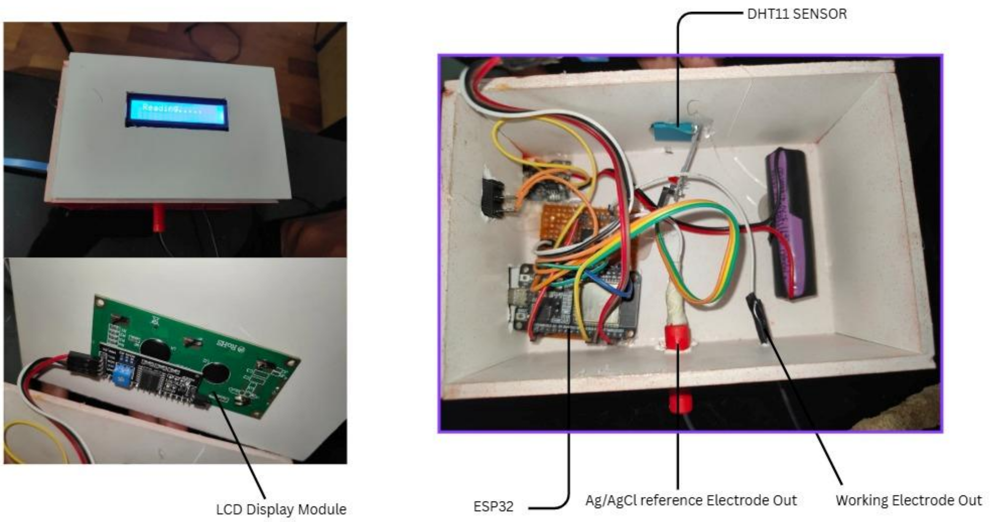

Fig.1: Corrosion detector prototype

3.2 SPECIMEN

The experimental investigation was carried out using steel reinforcement bars (rebars) of grade Fe415. A total of six rebars were used in the study, each having a uniform length of 48 cm. The selection of specimens was made to represent both controlled (non-corroded) and deteriorated (corroded) conditions of reinforcement typically found in reinforced concrete structures.

Out of the six specimens, four rebars were in non-corroded condition, consisting of two 8 mm diameter bars and two 10 mm diameter bars. These specimens were used as reference samples to represent reinforcement in its original, uncorroded state. The remaining two specimens were 10 mm diameter rebars that were heavily corroded and had been in service for approximately 10 years. These corroded bars were included to simulate aged structural conditions and to study the variation in electrochemical response compared to non-corroded reinforcement.

The combination of different diameters and corrosion conditions allows for a comparative assessment of corrosion behaviour under varying physical states. All rebars were prepared and arranged appropriately for half-cell potential measurement and environmental exposure during the experimental study. This selection of specimens ensures a realistic representation of field conditions and supports the evaluation of the proposed monitoring system.

Fig.2 (a): Heavily corroded 10 mm ϕ bar

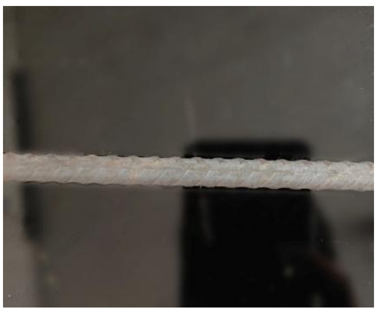

Fig.2 (b): Non corroded 10 mm ϕ bar

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3.3 WORKING OF PROTOTYPE

The developed prototype operates as a portable IoT-based corrosion monitoring device designed for simple field application. Initially, the device is powered on, after which the ESP32 microcontroller initializes all connected components, including the display module, DHT11 temperature and humidity sensor, and the half-cell potential measurement circuit. The device is then connected to a mobile phone hotspot using its built-in Wi-Fi capability, establishing communication between the hardware and the mobile application.

Once the connection is established, the user opens the mobile application and initiates the process by pressing the “Start” button. The device display then provides step-by-step instructions to guide the user. It first prompts the user to connect the electrodes to the reinforcement bar. The Ag/AgCl reference electrode is placed in contact with the concrete surface, while the electrical connection to the rebar is ensured. A delay of approximately 10 seconds is provided to allow proper stabilization and correct placement of the electrodes.

After this interval, the device automatically begins the measurement process. The half-cell potential reading is acquired over a duration of approximately 10 to 12 seconds to ensure stable and accurate values. The device applies a constant voltage of 1.6V. Simultaneously, the DHT11 sensor records the ambient temperature and humidity at the time of measurement. Once the data acquisition is complete, the device processes the voltage reading and displays the corrosion status on its screen as either “Corrosion Detected” or “No Corrosion.”

The measured electrode potential, along with temperature and humidity values, is transmitted in real time to the mobile application via Wi-Fi. The application displays these parameters clearly and also provides a corresponding indication of corrosion status. This integrated workflow ensures a user-friendly operation, enabling quick and reliable assessment of reinforcement corrosion without requiring complex instrumentation or manual interpretation.

Fig.3 (a): Ag/AgCl reference electrode

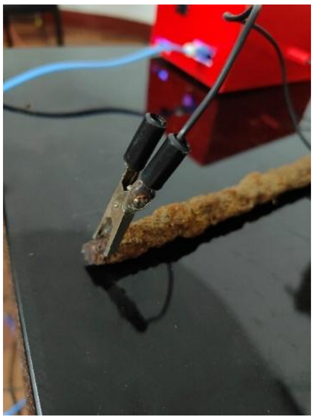

Fig.3 (b): Working electrode

Fig.3 (c): Test set-up

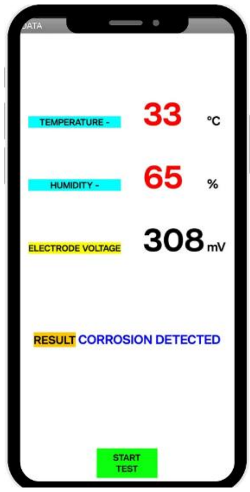

Fig.3 (d): Mobile app

3.4 DIGITAL TWIN MODELLING

The Digital Twin model for the proposed corrosion monitoring system was developed using Autodesk Revit 2026. The model represents the physical test setup in a virtual environment, enabling visualization of reinforcement condition based on real-time sensor data. A total of six reinforced concrete beam elements were created, each having dimensions of 100 mm × 100 mm × 500 mm. These beams were modelled individually to correspond with each test specimen used in the experimental study.

Each beam contains a single reinforcement bar placed centrally along its length. The reinforcement configuration consists of two 8 mm diameter rebars and four 10 mm diameter rebars, matching the physical specimens. The rebars were modelled using appropriate structural rebar tools within Revit, ensuring accurate geometric representation and positioning inside the concrete elements. Each beam-rebar unit was uniquely identified to maintain consistency between the physical specimens, sensor data, and the digital model.

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The Digital Twin model thus acts as a virtual representation of the physical system, reflecting the condition of each specimen in real time. By integrating sensor data with the BIM environment, the model enables efficient monitoring, quick identification of corrosion-prone elements, and improved understanding of structural behavior without the need for direct physical inspection.

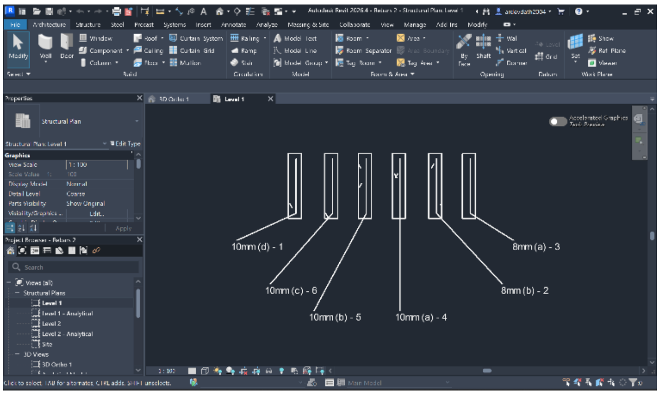

Fig.4 (a): Plan view

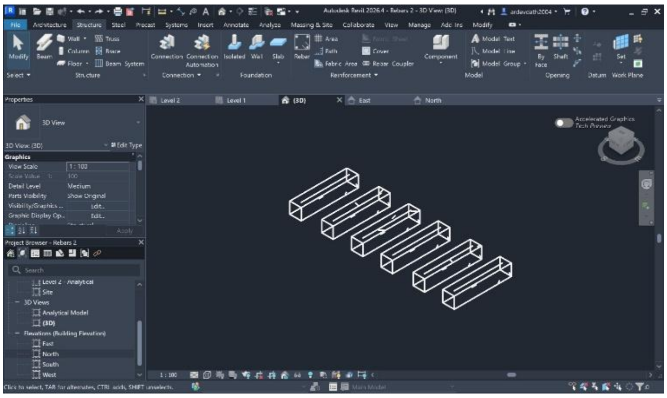

Fig.4 (b): 3D view

4. RESULTS AND DISCUSSION

The experimental evaluation of the developed prototype was carried out on a total of six reinforcement bars to assess its effectiveness in detecting corrosion. The specimens consisted of four 10 mm diameter bars and two 8 mm diameter bars, representing varying physical and corrosion conditions. For each specimen, half-cell potential, temperature, and ambient humidity were recorded using the developed IoT-based system. The results obtained from these measurements were used to determine the corrosion status of each rebar and to analyse the consistency and reliability of the prototype in identifying corrosion activity under different conditions.

Table 1: Test Results

S.No	Specimen		Temperature (˚C)	Humidity (%)	Electrode Voltage (mV)	Corrosion Status
1.	8mm bar	1	33	66	1638	No corrosion
		2	33	66	1664	No corrosion
2.	10mm bar	1	33	66	1663	No corrosion
		2	33	66	1662	No corrosion
		3	33	63	532	Corrosion detected
		4	33	65	392	Corrosion detected

5. CONCLUSION

The developed IoT-based prototype for corrosion monitoring of reinforcement in RCC structures was successfully designed, implemented, and tested. The system was able to measure half-cell potential along with environmental parameters such as temperature and ambient humidity, and transmit the data in real time to a mobile application. The integration of sensing, processing, and wireless communication enabled a simple and effective method for on-site corrosion assessment.

From the experimental results, it was observed that the prototype was capable of clearly distinguishing between corroded and non-corroded reinforcement bars. The 10 mm bars identified as corroded exhibited significantly lower electrode voltage values (392 mV and 532 mV), while the non-corroded bars showed consistently higher values (above 1600 mV). This variation in potential readings aligns with the fundamental principle of half-cell potential measurement, confirming the reliability of the system in detecting corrosion activity.

The results also demonstrate that the system provides consistent readings under similar environmental conditions, as temperature and humidity remained nearly constant throughout the tests. The corrosion status displayed on both the device and mobile application corresponded accurately with the observed condition of the rebars, indicating effective data processing and interpretation.

Overall, the prototype proves to be a cost-effective, portable, and user-friendly solution for real-time corrosion monitoring. It reduces dependency on complex laboratory equipment and manual interpretation, making it suitable for field applications. The system has the potential to support early detection of corrosion in reinforced concrete structures, thereby contributing to improved maintenance planning and enhanced structural durability

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