Development of a Formwork Deflection Measurement System for Construction Site Safety and Quality Assurance

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Abstract

In this study a low-cost real-time monitoring system to detect deflection of scaffolding for the formwork is designed and it is implemented on construction sites. The developed system uses HC-SR04 ultrasonic distance sensors to measure the distance between the ground and the ceiling formwork. Successive distance measurements relieve the deflection of scaffold components and the data is transmited to a central computer via 433 MHz RF modules. The distance measurements are based on the speed of sound and in order to enhance the accuracy of the measurements a DHT11 temperature sensor is incorporated into the system to account for temperature induced changes in speed of sound. The use of low-cost, easily replaceable sensors ensures usability of the developed system on construction sites where against environmental conditions such as physical impacts and heavy dust are commonly encountered. The ultrasonic sensors are activated sequentially to reduce interference and more accurate distance measurements are obtained. The system is designed to ensure easy installation which makes it adaptable to various construction environments. The distance data collected by the sensors are processed through a central computer. Recent measurements with baseline data gathered at the beginning of the concrete placement process are compared. This assists detecting significant changes on the scaffolding system such as excessive settlement or deformation, which could jeopardize the safety of the formwork structure. The proposed system offers an efficient, cost-effective, and scalable solution for real-time monitoring of the deflection of the scaffolding for the formwork. Consequently it ensures structural stability, construction safety, and quality of concreting tasks.

1. Introduction

Concrete placement tasks contain challenging quality and occupational health and safety issues. Collapse of the scaffolding for the formwork is a frequent accident type that can be seen at the construction sites. Before the collapse the formwork undergoes excessive deflections which can be an early warning. In the literature deflection of the formworks has not been monitored real time. Therefore this study aims to address the aforementioned literature gap.

1.1 Motivation

Reducing the risks and solving the negativities can be solved by utilizing the existing measurement technology. Advances in sensor technologies have made it technically and economically feasible to monitor and control formwork deflections in real time. This study aims to measure the deflections of the formwork that could be encountered during concrete placement by using ultrasonic distance sensors.

The proposed system requires the monitoring of the deflection amounts of the formwork in real time to enable rapid intervention in case of exceeding the specified deflection limits. Ultrasonic distance sensors provide accurate and precise distance measurements with high repetition frequency. Moreover their low cost, easy installation features and reliable performance makes the aforementioned distance measurement technique suitable for the implementation at the construction sites. The sensors are placed on the slab directly under the installed scaffolding for the formwork before the concrete placement. The proposed system can assist the civil engineers to prevent material losses, to ensure occupational safety and optimize project costs, as well as to increase quality of concreting tasks conducted at the construction site.

In this way, it is aimed both to increase quality standards and to strengthen occupational health and safety measures at the construction sites. In particular, the detection of excessive deformations that may occur during concreting processes is critical in terms of preventing possible material losses and occupational accidents.

The dynamic nature of construction sites and their constantly changing backgrounds complicate the sensor calibration of image-based methods and reduce the efficiency of these systems.

433MHz RF Transceiver Module is frequently preferred in wireless communication projects due to its low cost, energy efficiency and easy use. The module can be easily integrated with microcontrollers such as Arduino and Raspberry Pi, its transmission performance can be increased with additional antenna, and data security can be ensured with encryption methods. These features create a wide range of applications from do it yourself projects to industrial applications.

Moreover, instantaneous monitoring of deflection measurements will allow taking precautions to improve the quality of workmanship and to optimize the concrete placement process. Keeping the concrete placement process under control will ensure that reinforced concrete structures are completed in accordance with the desired durability and quality standards.

1.2 Low Cost Real Time Measurement

Thanks to the developments in sensor technologies, it has become technically and economically feasible to monitor and control formwork deflections in real time. In this study, it is aimed to improve both construction quality and safety measures by evaluating the formwork deflections during concrete pouring by means of ultrasonic distance sensors to be placed under the scaffolding for the formwork to be installed for concrete

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pouring. There are many radio and image-based studies on construction safety. Since radio-based methods require the placement of signal transceiver devices on objects, it is costly and troublesome to place multiple devices on construction sites. Similarly, it is difficult to calibrate the sensors of vision-based methods due to the dynamic nature of construction sites and their constantly changing backgrounds. Detection of excessive deformations that may occur in concreting processes is critical to prevent possible material losses and reduce occupational accidents. In order to improve construction safety, radio frequency (RF) is often preferred in wireless communication projects due to its low cost, energy efficiency and ease of use. The low cost and easy installation features of ultrasonic distance sensors provide significant advantages for use on construction sites. With the utilized method, the deflection amounts of the formworks can be monitored in real time and the necessary precautions can be taken more quickly when the specified deflection limits are exceeded. Halting the construction immediately and evacuating the concreting zone can be listed as the precautions to be taken. Thus, safety will be ensured at the construction site, possible material losses and occupational accidents can be prevented. Instant monitoring of formwork deflection measurements and making necessary interventions will also enable optimization of workmanship quality and concrete placement. Keeping the concrete casting process under control will ensure that reinforced concrete structures are completed in accordance with the desired durability and quality standards; thus, it will contribute significantly to the achievement of both technical and economic targets of the projects.

1.3 Literature Review

Reinforced concrete building construction is undergoing a noteworthy transformation process in line with developing construction technologies and methods. Formwork systems have a critical role in terms of the quality, durability and shortening of construction time of structures. Formwork systems provide casting for the shape and dimensions of the structural elements during the casting and hardening process of concrete. Formwork engineering is a critical process for concrete structures, and the formwork systems directly affect the overall performance and environmental impacts of the structures. Selection of the appropriate formwork affects the aesthetic appearance, durability and cost-effectiveness of the structures. Moreover, the efficiency of formwork systems directly effects the duration of reinforced concrete construction and the labor costs (Li et al., 2022). Limitations on the budgets and increasing concerns on the environmental problems intensified the importance of sustainable construction practices. Nilimaa et al. (2023) examined the impact of utilized formwork systems on the environment by taking into account sustainable construction practices.

Huang et al. (2000) developed a system for early detection of possible structural deflections of formwork systems. The proposed system aims to improve the safety precautions of formwork systems with excessive height. The system provides important aid to prevent any formwork failure as the fresh concrete applies important magnitudes of lateral pressure to the formwork when the height of the shear walls and columns are high. The developed monitoring method also increases the durability of structures and improves the occupational health and safety standards. Leung and Cao (2010) developed a pseudo-ductile permanent formwork system for the reinforced concrete structures. The developed system functions as a permanent formwork and provides high mechanical strength as well as extensive deformation tolerance. The advantages of the pseudo-ductile permanent formwork system can be listed as its durability, lightness, flexibility, and sustainability.

Formwork systems used during the construction of concrete structures have important impact on the quality of construction since the utilized formwork system should be capable of preserving the form of the structure. Moreover, dismantling process of the formwork should not deteriorate the surface of the hardened concrete. Permanent (stay-in-place) formwork systems avoid the dismantling procedure of the formwork task. This benefit accelerates the construction processes and reduces labor costs, therefore permanent formworks were examined extensively in the literature. Kim et al. (2020) studied the load-deflection behavior of concrete slabs constructed by Textile Reinforced Concrete (TRC) formwork. TRC formworks are produced from special textile fibers having high tensile strength and low weight. Strength and durability of TRC ensures the long service period of the structure. Moreover, special tie mechanism ensures the stability of the formwork during the concrete casting process. The wider utilization of TRC formwork systems in the construction sector indicates the great potential of the TRC formworks in terms of both structural safety and economic efficiency.

Liew et al., (2018) developed a prototype rod-web formwork system and tested its mechanical properties and structural behavior. The prototype was produced by integrating high-strength rods to form a web kind structure. The end product functions as a formwork and increases the load-carrying capacity of the structural elements. The active control mechanism responds to load changes throughout the structural elements via sensors and actuators. Overall the developed system ensures the stability of the structure.

According to a survey conducted by Ahmed et al. (2012) 50% of the respondents stated that the utilized formwork system has important impact on the sustainability of the project. Moreover construction economy has considerable importance. This situation reveals importance of the formwork systems to achieve sustainability goals. Therefore, the manufacturing of sustainable formwork systems is a critical step to reduce the environmental impact of the construction.

IoT technologies have wide-ranging applications to conduct sustainable construction projects. IoT is being used in various areas to achieve energy efficiency, optimize resource use and reduce environmental impacts by the construction industry. To illustrate, real-time monitoring systems and building information modeling (BIM) technologies help project managers to manage projects effectively. The mentioned techniques are also implemented to reduce wastes and ensure efficient use of resources. These applications ensures fulfillment of environmental sustainability goals and reduces construction costs. In addition, relevant sensors can predict equipment maintenance requirements, reduce repair times and increase business continuity. IoT applications can be implemented to prevent occupational accidents and improve safety conditions of the construction sites (Oke and Arowoiya, 2021).

Sustainable construction aims to reduce environmental impacts of the construction process, increase the efficiency of the resource allocation, and improve the life quality of the residents. IoT can improve the sustainability of buildings by increasing the efficiency of the construction processes. IoT technologies can monitor energy consumption of buildings and collected data can be analyzed and used to improve energy efficiency of the building. Continuous energy consumption monitoring can assist the early detection of the anomalies and prevent energy wastes. IoT implementations can optimize material storage and consumption processes as well as reduce material wastes by continuously monitoring the material delivery and storage tasks throughout the construction process. Efficient reporting and tracking of the materials that are vulnerable to deterioration assist in reduction of the construction wastes. Moreover, IoT devices can monitor construction crews and construction machines at the construction site and prevent accidents with collision detection algorithms. IoT can improve the sustainability of buildings by monitoring their performance and optimizing maintenance and improvement processes. The listed applications demonstrate the potential aids provided by IoT to ensure sustainability in the construction industry (Li et al. 2018).

Implementation of IoT systems on construction sites even equipped with low-cost sensors makes the construction processes more efficient and safe. These sensors provide continuous monitoring and improve safety by collecting accurate real-time data from the construction site. The use of low-cost sensors offers significant cost savings compared with the traditional monitoring systems. Furthermore, low-cost sensors increase the reliability of the system by enabling frequent sensor replacements. Real-time continuous monitoring of the construction site facilitates taking safety precautions by early detection of potential risks that might occur on the construction site. Furthermore, material usage, labor and time management can be optimized more efficiently through real-time data collection. IoT applications at the construction sites ensure the sustainability and safety of construction processes by providing an effective solution for monitoring construction projects (Nguyen et al. 2020).

IoT-based sensors which detect high temperature, gas leak, or equipment malfunctions can significantly enhance workplace safety. The listed sensor types continuously monitor the construction site and the collected data is analyzed real-time to detect any hazardous situation. These sensors can detect potential risks early and send immediate alerts to workers who were working nearby. Moreover, the log data can be investigated to detect any responsibility of the workers that cause the event. Consequently, the IoT monitoring systems will ensure construction workers take precautions and prevent workplace accidents and safety violations. Additionally, IoT devices continuously monitor workforce performance, equipment usage, and material consumption. The collected data can be utilized to improve the efficiency of construction processes. Through real-time data collection and monitoring, managers can oversee project progress more effectively and intervene promptly to optimize workflows. These technologies not only enhance resource utilization on construction sites but also ensure timely project completion. Implementation of IoT creates a safer and more efficient working environment for the construction sector (Khan et al., 2024).

IoT-based sensors and devices enable real-time monitoring of various ongoing activities of construction projects in real time. The collected data is stored on a central computer that allows remote access for managers. Cloud data technologies simplify management of construction processes by tracking workforce productivity, material usage, and safety risks. Moreover, detailed data collected by IoT devices enable managers to oversee construction projects without being physically present on-site. This feature allows the project managers to direct several construction projects located at distant regions. The aforementioned remote monitoring, inspection and interfere capability facilitate faster project completion, and enhance safety. Consequently, the flexibility and efficiency provided by IoT for construction managers and site engineers makes construction processes more synchronized and effective (Bucchiarone, A., 2019).

IoT sensors enable real-time monitoring of various events and cases that occur at the construction sites. The data collection items cover materials, workforce, equipment status, and environmental conditions. Moreover, IoT implementations ensure collecting the up-to-date data for Building Information Modeling (BIM) applications. This integration allows managers to monitor the construction process digitally without being physically on-site, while the real-time data flow enhances project management efficiency. Ability of IoT technologies to digitally track all aspects of construction processes enables better resource utilization, improved workforce productivity, and reduced safety risks. The data collected from IoT sensors can be integrated into the BIM model. This allows project managers to assess current job conditions promptly. Also it provides opportunities for early intervention. This integration of data collection and analysis supports the completion of construction projects timely and within budget (Tagliabue et al., 2018).

Literature review reveals that real-time data collected on construction sites is predominantly valued and stored within BIM frameworks, demonstrating significant gains in occupational safety and quality control. However, the risks associated with deflections of the formwork during the placement of fresh concrete, have not been extensively studied. Beside the aforementioned accidents may pose important safety hazards and quality issues. To address this literature gap, a system has been designed which is easy to deploy on construction sites, cost-effective, and capable of conducting high accurate measurements. Preliminary trials of this system have been conducted. Following sections of the paper illustrates the implemented roadmap during the design of the system, and selection criteria of the hardware components. Also at the case study section a demonstration of its use at a construction site is presented.

2. Methodology

A low-cost real-time monitoring system directed by Arduino microcontroller has been developed to real-time monitor the stability of the scaffolding for the formwork. The proposed system consists of an array of ultrasonic distance measurement sensors, a DHT11 temperature measurement sensor, an Arduino Leonardo microcontroller, and a radio frequency (RF) module for wireless data transmission. The primary objective of the developed system is to measure the elevation of scaffolding for the slab formwork and detect any abnormal deflections by comparing the successive distance measurements. The system continuously compares the successive distance values and aims to detect deflections of the slab formwork throughout the concreting task. The data flow model of the system is illustrated in Figure 1.

HC-SR04 ultrasonic distance measurement sensors are used in the system due to their low cost. In construction sites, sensors are highly susceptible to dust particles, physical impacts caused by collision, material fall, and stepping on of the construction worker. Therefore, low-cost hardware was preferred to facilitate the replacement of sensors economically. Ultrasonic distance measurement technique measures the time of flight of the sound waves and multiplies the flight time with the speed of sound to compute the distance. Speed of sound is affected by the temperature of the medium. For this reason one DHT11 temperature sensor is employed to measure the temperature of the medium and compute the speed of sound accurately.

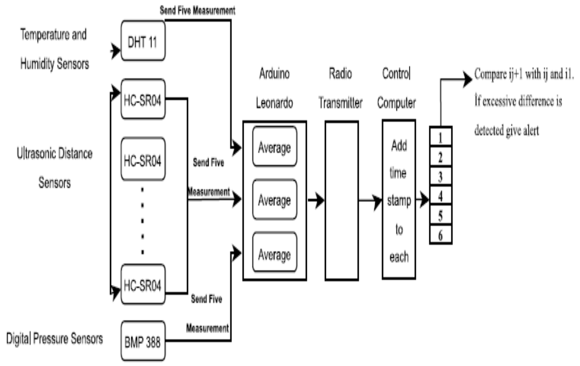


Figure 1. Data acquisition and transmission components of the proposed system.

Cost-effective RF transmitter and receiver modules which can provide practical communication capabilities were utilized. Wireless communication devices cannot always work properly at construction sites due to electromagnetic interference, environmental obstacles, and insufficient data transmission range. However, RF modules are well-suited for the challenging environmental conditions of construction sites, due to their low energy consumption, long data transmission rate and ease of installation. Additionally, cheap price of the radio transmitters enable rapid and cost-efficient system repairs in case of failures. Correctly and timely transmit and receive the measurement data from the transmitter to the receiver as well as to a central computer plays a critical role in ensuring the overall performance and reliability of the system. Radio Frequency data transmission modules are programmed by the VirtualWire library to ensure reliable data transmission. The RF transmitter and receiver modules are depicted in Figure 2.

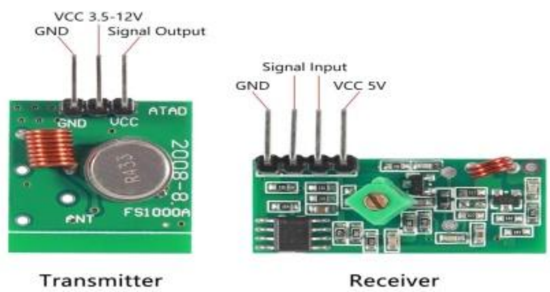


Figure 2. Utilized 433 MHz radio frequency transmitter and receiver modules.

The system components have been designed to be easily installable and portable. Figures 3 and 4 illustrate the circuit diagrams for both the transmitter and the receiver modules of the system. As illustrated in Figure 3 the transmitter module contains six ultrasonic distance measurement units, one temperature measurement unit and one RF transmitter.

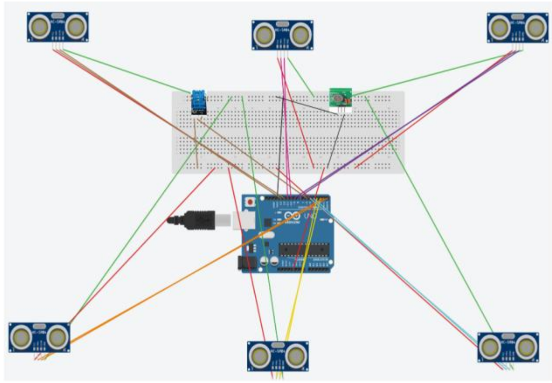


Figure 3. Transmitter and measurement module of the proposed system.

The obtained measurements are transmitted to the receiver real time. The measured data is six distances in mm and one temperature value in centigrade. All the transmitted data are integer numbers and each data package is sent every second.

Figure 4 illustrates the receiver module of the system. It is simpler than the transmitter as it only encompasses 433 MHz RF receiver and an arduino microcontroller. The received data is transmitted to a desktop computer by serial connection and saved by adding time stamp for each measurement. The accumulated data can be evaluated real time by monitoring the distance between the senors and the framework. It is expected that the formwork deflects under the weight of the fresh concrete. It is known that within 2 and 2.5 cm deflection of the formwork is within acceptable limits. If higher deflections are detected, the system will alert the site manager.

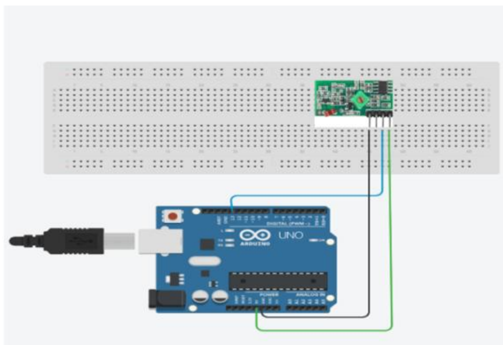


Figure 4 Receiver module of the system.

Figure 5 demonstrates the installation phase of the system at the construction site. In Figure 5, the Arduino project, which includes ultrasonic distance measurements, is located within the red oval circle, indicating the setup of the transmitter. The installation of the system can be completed within minutes. A rechargeable fully charged 9V battery can provide the necessary power throughout the concreting process.

Figure 5. installment of the system at a construction site.

General list of the components of the system including its technical specifications and price are given in Table 1.

The HC-SR04 ultrasonic distance measurement sensors, which are the core components of the proposed system, emit sound waves through a 10-microsecond signal pulse sent from the trig pin. These waves reflect off a surface and are detected via the echo pin. The time taken for the echo to return is measured using the pulseIn function, and the distance is calculated using the following formula:

$$\text{Distance(mm)} = \frac{\text{Time}}{(331.5+0.606*T)*2} * 100 \qquad (1)$$

To ensure accurate measurements by the sensors, it is necessary to correct errors that may arise from the variation of the speed of sound with temperature. To address this, the speed of sound is calculated by taking the temperature of the medium by Eq. 2.

$$c=331.5+0.606*T \qquad (2)$$

In Eq 2, T represents the ambient temperature measured by the DHT11 sensor. This adjustment has enhanced the reliability of the system, particularly under varying temperature conditions in outdoor construction sites.

Component	Specifications	Usage Purposes	Ave. Price (€)
433MHz RF Transmitter-Receiver Module	-Frequency: 433MHz - Range: 100–500 meters (open space) - Transmission Speed: Up to 4.8kbps -Power Consumption: Low	Wireless data transmission, remote controls, IoT applications	2–3
HC-SR04 Ultrasonic Sensor	-Sensing Range: 2–400 cm -Accuracy: ±3mm -Operating Voltage: 5V -Angle of Detection: ~15°	Distance measurement, obstacle detection, robotics projects	1–2
DHT11 Temperature and Humidity Sensor	- Temperature Range: 0–50°C (±2°C accuracy) - Humidity Range: 20–90% RH (±5% accuracy) - Output: Digital signal	Environmental monitoring, temperature and humidity tracking	1–3
Arduino Leonardo	Microcontroller: ATmega32u4 -Operating Voltage: 5V -Digital I/O Pins: 20 (7 with PWM capability) -Flash Memory: 32 KB	Prototyping, USB-based applications, keyboard/mouse emulation	10–12

Table 1. Materials Used and Their Properties.

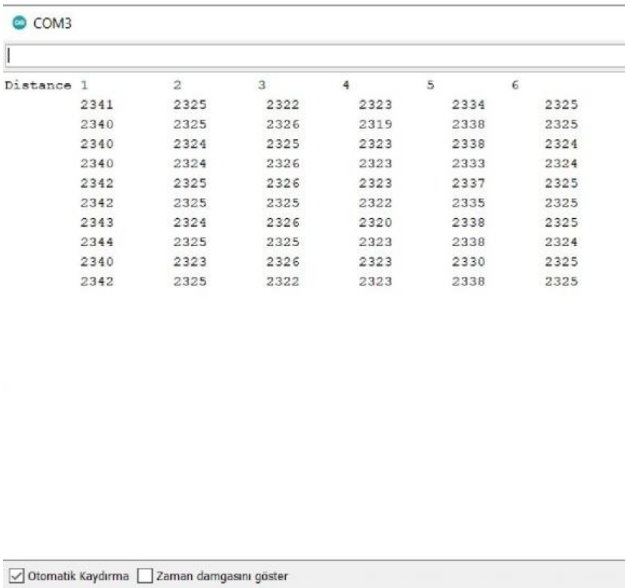
The simultaneous operation of ultrasonic sensors can lead to interference of sound waves and measurement errors. Therefore, each sensor is triggered sequentially, and five measurements are made for each reading. These measurements are averaged to obtain more reliable and stable results. The measurement cycle is completed within 10 milliseconds for each sensor. Aforementioned duration is sufficient to quickly detect the deflections of the scaffolding for the formwork during the concreting process. The measured distance data is transmitted to the central computer via the RF module. The messages are sent in the following format:

M1:xx, M2:xx, M3:xx, ..., M6:xx, Temp:yy

Here, M1 through M6 represent the distances measured by the sensors, while Temp denotes the ambient temperature. The VirtualWire library, used for data transmission by the RF module, was chosen for its low energy consumption and reliable data communication. After the data is received, it is processed by software running on the central computer.

On the central computer, the received distances are compared to the previous measurement values to analyze the stability of the scaffolding. The algorithm expects the telescopic support columns of the scaffolding to shorten due to the weight of the concrete. If the total deflection exceeds 20 mm, the scaffolding is considered to be at risk of collapse. Additionally, if the concrete is not evenly placed, there may be upward deflection (rise) around the concrete areas. The algorithm takes the aforementioned affect into account by analyzing data consistency with each measurement, and alerts the user when anomalies are detected.

Real-time measurements are transmitted to the central computer via the RF 315/433 MHz Transceiver Module. Sample transmitted data is shown in Figure 6.



Distance 1	2	3	4	5	6
2341	2325	2322	2323	2334	2325
2340	2325	2326	2319	2338	2325
2340	2324	2325	2323	2338	2324
2340	2324	2326	2323	2333	2324
2342	2325	2326	2323	2337	2325
2342	2325	2325	2322	2335	2325
2343	2324	2326	2320	2338	2325
2344	2325	2325	2323	2338	2324
2340	2323	2326	2323	2330	2325
2342	2325	2322	2323	2338	2325

Figure 6. Real time transmitted data.

The obtained measurements are analyzed by an algorithm running on the central computer. The algorithm compares the acquired distance measurements with the initial measurement taken when the concreting process begins. Additionally, consecutive measurements are also compared. It is expected that the telescopic support columns of the scaffolding will shorten due to the weight of the placed concrete. The shortening should not exceed 20 mm; otherwise, the scaffolding may collapse. Furthermore, unless self-compacting concrete is used, concrete remains viscous. Therefore, if workers fail to lay the concrete evenly due to the effects of load distribution, areas adjacent to the concrete placement site may experience upward deflection. The algorithm takes these effects into account.

3. Conclusion

This study aims to develop a low-cost and practical system for real-time monitoring of the stability of the scaffolding for the formwork at construction sites. The HC-SR04 ultrasonic distance sensors used in the system were selected for their cost-effectiveness. Harsh construction site conditions are expected to cause frequent replacement requirements and low cost of the sensors would not cause any burden. To minimize error margins caused by environmental conditions, the data obtained from the sensors were analyzed alongside temperature readings from the DHT11 temperature sensor. The sensors were operated sequentially and individually to reduce noise effects and the accuracy of the measurements was enhanced by averaging multiple data points collected in each measurement cycle.
Communication between the transmitter and receiver units was established by 433 MHz RF modules. The Amplitude Shift Keying (ASK) method was employed for data transmission, simplifying the process and making it energy-efficient, thus enabling the system to operate with low power consumption over extended periods. The wide coverage range of the RF modules allows seamless communication with the central computer and facilitates real-time data monitoring and processing. Furthermore, the algorithms were designed to detect deflections of the formwork caused by potential shortening of the telescopic poles of the scaffolding as well as upward deformations caused by the weight of the concrete poured at a nearby location.

The proposed system is designed to shorten the response time of the monitoring system to react for any indication that could lead to the collapse of the scaffolding for the formwork. Consequently, the system should have the capability of timely detection of the abnormal deflections of the formwork and the scaffolding. The real-time monitoring provided by the developed system enables tracking the amount of deflections of the formwork components. The velocity of the deflection and the exact location of the formwork where concrete have been being placed can be assessed together to decide on the state of the scaffolding and the formwork. Specifically, the immediate detection of excessive deflections of the formwork during the concrete placement is critical for both safety of the workers and the integrity of the structure.

The developed system offers a practical and cost-effective solution for construction sites. The use of low-cost sensors ensures that the system can be easily repaired and replaced in case of sensor failure. Additionally, the installation and operation processes are quick and simple. As a result, the system can prevent accidents and reduce safety risks. Furthermore, the proposed system provides an effective tool for monitoring the state of scaffolding and formwork.

The proposed system offers an economic, reliable, and portable solution to improve the safety of concreting tasks. On site preliminary tests and implementations have demonstrated that the system operates steadily under varying temperature. Real-time detection of deflections of the scaffolding elements during concreting is critical to prevent collapse of the formwork. Furthermore, this system has proven its applicability in large-scale construction projects even though it is composed of low-cost components. Fast and straightforward installation property of the system provides advantages in terms of labor and cost. This system is designed to enable further studies which will assemble more capable sensors and utilize more advanced algorithms in the future.

Total price of the used distance measurement sensors, communication hardware, microcontroller board, and assembling hardware is around $40. The low cost of the system makes the implementation at large construction sites economically feasible. The system does not require any specialized technical knowledge to set up and deploy. This property makes it an ideal solution for construction projects of various scales. Additionally, quick replacement of the components repair in the event of damage can be achieved easily due to the low cost of the sensors.

A low-cost and user-friendly system to measure the deflections of the scaffolding and formwork is developed to enhance safety and efficiency of concreting tasks. The developed system offers significant contributions both academically and industrially when the increasing demand for real-time monitoring systems in the construction sector is concerned. Future work could explore the integration of different sensor types and the transition to cloud-based data analysis to expand the proposed system’s capabilities.

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