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Study on Health Monitoring of Concrete Structures Using Wireless Sensor Networks

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Abstract. In this study, a system for monitoring the structural health of bridge deck and predicting various possible damages to this section was designed based on measuring the temperature and humidity with the use of wireless sensor networks then it was implemented and investigated.

This paper also presents the experimental development of an automatic wireless sensor monitoring system for concrete structures. The objective is to provide a solution to measure both temperature and humidity inside a concrete structure. The research has been focused in the early age and curing phase period. Four solutions have been addressed.

The first one involves the use of a negative temperature coefficient thermistor and an IRIS mote allowing for the creation of an IEEE 802.15.4 network. The second one considers the use of the SHT15 sensor, together with the PIC18F4680 microcontroller or the Arduino platform. The third solution involves the use of the SHT21S sensor and the eZ430-RF2500 wireless development tool platform for the MSP430 microcontroller. Finally, the fourth solution considers both the SHT15 and SHT21S sensors completely shielded allowing for the creation of a long-term solution. The potential of applying the proposed inexpensive wireless sensor network approach is completely investigated and verified.

Keywords: Structural health monitoring, wireless sensor networks, concrete, sensor, temperature, humidity.

1. Introduction

Maintaining the safety and reliable service of a large bridge over its relatively long life requires obtaining continuous and reliable data regarding its structure, including the damages which are caused by the temperature gradient, cracking, fatigue, corrosion of structures and the decrease of load capacity of the bridge, etc. They all should be carefully evaluated. Common measurements such as periodic visual inspections and controlled loading test are typical in this respect and their limitations and disadvantages have been thoroughly investigated.

A new technology called structural health monitoring (SHM) which use wireless sensor networks [1]-[8] has recently attracted a lot of attention in the field of measurement and analysis of those mentioned factors. There are various SHM systems that can detect damages of the bridge structure through analyzing the dynamic characteristics of the bridge [9], [10].

In this study, a SHM system which utilizes the wireless sensor networks (WSN) and is based on monitoring humidity and thermal responses of environment has been designed and analyzed with the help of a hypothetical bridge. Researchers claim that this method has the ability to bypass the problems and limitations of the other SHM methods [11], [12]. Exposure to sun and heat exchange with the environment leads to temperature differences in different parts of the bridge. Such changes occur continuously and slowly every day and affect the structure of the bridge [13], [14]. The temperature difference between the different parts leads to the thermal response of the bridge including thermally induced strains, stresses, and changes in the reactions of bridge piers [15]. The change of these responses is slow, so they can be easily distinguished from the thermal responses caused by temporary traffic. Furthermore, they have many measureable effects. In the case of pre-stressed concrete bridges, thermally induced stresses are usually in the same range of live load stresses but are often greater than these stresses [16]-[22].

In view of the above discussion, a SHM based on environmental thermal responses seems suitable for long bridges with several curves. The main focus of this research is on pre-stressed reinforced concrete bridges with medium to high curve lengths. This study also examines the evaluation and monitoring of effects of humidity on different parts of the bridge and also the corrosion and damage caused by humidity or those damages for which humidity act as accelerating factor. The results showed that a well-designed and well-implemented SHM system based on environmental thermal responses and humidity has the ability of detecting structural damages and identifying their location and their severity [23]-[25].

The second section of this article introduces the details of proposed SHM system and its implementation, hardware, configuration of sensor network and developed monitoring program. The third section, which is the primary objective of this interdisciplinary research, is to develop a prototype for Wireless Sensor Networks allowing for remotely monitoring certain concrete structures , through testing several kinds of sensors that have the capability to be matched with the proposed SHM system and investigating their properties, accuracy, reliability and limitations in SHM of concrete structures.

From the application perspective, WSNs are useful in situations that require quick or infrastructure-less

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deployment and continuously monitoring [26], [27]. Temperature is an important parameter during the curing and hardening of the concrete, since the concrete cannot be too cold or too hot. When the temperature decreases, the hydration reaction slows down. Hence, if the concrete temperature increases the reaction accelerates, creating an exothermic reaction -which itself produces more and more heat- causing temperature differentials within the concrete. This temperature gradient can lead to cracking. Moreover, during the initial phase of the life of the concrete, it is essential to avoid cracking caused by the rapid drying due to increased temperature and the on-going hydration reaction. The fourth section summarizes the results, the discussed issues, the advantage and disadvantages of the proposed SHM method.

2. Proposed SHM System

A. Description of Proposed SHM System, Components and Principles

In this paper, a SHM system with special characteristics was designed as shown in Fig. 1, then it is implemented and verified for a hypothetical bridge.

As shown in Fig. 1, parameters of temperature and humidity are monitored at two points of the bridge deck. This data will be used for data mining process and the prediction of critical values for the following days, and a warning system based on fuzzy inference techniques will assess the status of mentioned points and will announce timely pre-emptive alerts to the maintenance team of the bridges.

B. Description of Hardware and Wireless Sensor Nodes

Inexpensive and analog sensors of LM35 and HIH4000 were used for sensing and measuring the temperature and humidity respectively for the design of nodes of wireless sensor network. To assess the reliability and accuracy of the system, wired SHT11 sensor was used to obtain the temperature and humidity data in the desired nodes. This sensor calculates the humidity and temperature with high precision in digital form and does not need signal conditioning. A USB DAQ Digital Sensor was used to obtain its information. Sensor nodes were designed with Protel (Altium Designer) software. This design includes a board for LM35 and HIH4000 analog sensors and a separate board for SHT11 sensor which is considered as a reference for measurement. They are shown in Fig. 2 and Fig. 3, respectively.

In the next step, “ProBee-ZE10 ZigBee” module was used as wireless module. The default development board of this device was used to ensure easier application and also for easier installation of the connectors. Three selected wireless modules were configured. Two modules were defined as “end device” and one module was defined as “coordinator”. Configuration of end devices and coordinator was performed through USB terminal of a laptop and by the use of “Hyper Terminal” software.

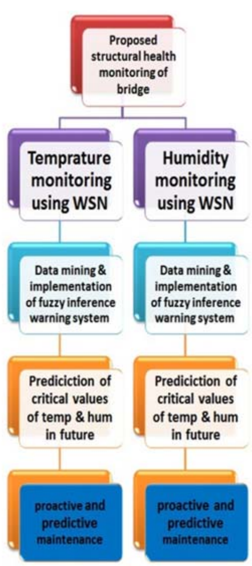

Fig. 1. Overview of the proposed SHM systems and its components & functions.

3. Experimental Work

A. Negative Temperature Thermistor–Temperature Sensor

The first set of tests consisted of measuring the temperature with a NTC temperature sensor inside a concrete cube (common strength class C25/30, 10 cm length size).The acquisition system consists of a Sensor Board and an IRIS mote, facilitating the creation of an IEEE 802.15.4 network whose primary function is to remotely collect the data from the NTC sensor inside the concrete cube.

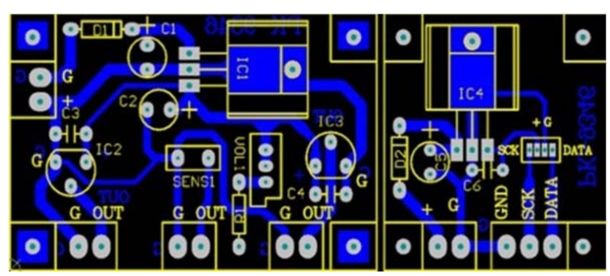

Fig. 2. layout of PCB of board and bias circuits of temperature and humidity sensors.

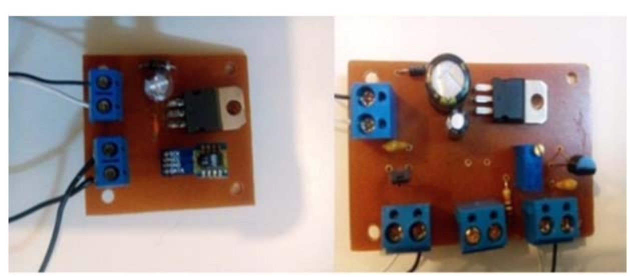

Fig. 3. The final layout of sensor nodes (Analog nodes including LM35 and HIH4000 sensors on the right side, and SHT node on the left side).

B. SHT15 Humidity and Temperature Sensor

In the second set of tests, the SHT15 digital sensor was used, facilitating to measure both temperature and humidity with high accuracy in a single chip sensor. Fig. 4 presents a schematic representation of process to measure the temperature and humidity within the concrete cube.

The conversion from the raw value returned by the SHT15 sensor, R_{xval}, to the temperature and humidity values was performed by using the following equations:

$$\text{Temperature [}^\circ\text{C]} = 0.01R_{xval} - 40 \quad (1)$$

$$\text{Humidity [\%}RH\text{]} = -0.4 + 0.0405R_{xval} - 0.0000028\,(R_{xval})^2 \quad (2)$$

Before inserting the sensor inside the concrete block, the sensors were placed inside a small size cube (4 cm side length) made of cement mortar for its protection.

C. SHT21S Humidity and Temperature Sensor

1) Standalone Version

Besides the SHT15 sensor, we tested the new Sensirion SHT21S (humidity/temperature) sensor. Before testing this sensor a cement mortar shell has been used for its protection. This sensor is an updated version of the previous one but with a smaller package. To test this sensor, an acquisition system was designed to facilitate the acquisition of the analogue signal while converting it for its digital representation. As previously mentioned we intend to measure both temperature and humidity inside the concrete block, from the early ages, during setting and hardening period. The temperature and humidity values are obtained by using Eqs. (3) and (4) respectively:

$$\text{Temperature [}^\circ\text{C]} = -46.85 + 175.72 \times \frac{V_{SO}}{V_{DD}} \quad (3)$$

$$\text{Humidity [\%}RH\text{]} = -6 + 125 \times \frac{V_{SO}}{V_{DD}} \quad (4)$$

where VDD is the supply voltage at which the SHT21S sensor works, as presented in the datasheet of the sensor in the interface specifications. In this case, VDD = 3 V. Besides, since the SHT21S output is a Sigma Delta Modulated (SDM) signal, normally this signal is converted to an analogue voltage signal by the means of a low-pass filter. The output of low pass filter provides a voltage value (VSO) which is a portion of VDD, depending on the measured humidity or temperature. The developed acquisition system (for the standalone SHT21S) incorporates a micro SD module, responsible for storing the values acquired from the SHT21S sensor, as shown in Fig. 5.

The “MSP430F449-STK2” module was used to convert the signal output from the RC-filter to the digital format. The algorithm running inside the microcontroller performs five readings (with a 100 ms interval between two consecutive readings for the temperature), storing the fith reading in a buffer. Then, it switches to the humidity sensor, performing another five readings and conversions with the same duration between consecutive readings, storing the fifth reading in another buffer. Finally, after that it sends the commands to store the temperature and humidity values in separated text files, into the micro SD card.

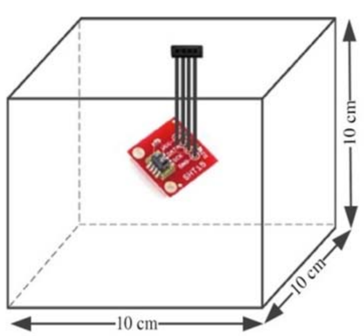

Fig. 4. Schematic representation of temperature and humidity sensor inside a concrete cube.

2) Wireless Version

The SHT21S wireless prototype aims at creating a Building Wireless Sensor Network (BWSN) capable of measuring temperature and humidity inside a concrete structure. It has two Integrated Circuits (ICs) interfaces via Serial Port Interface (SPI), and an antenna allowing for connectivity with no additional hardware components. Besides, it provides real-time data information and remote interaction with multiple devices (e.g., laptop, PDA, cell phone with ZigBee capabilities). The “MSP430F2274” ultra-low-power microcontroller controls the “CC2500” radio transceiver-that operate at the 2.4 GHz band-and establishes a basic wireless network with minimal power requirements, enabling to extend the system lifetime. Fig. 6 presents the acquisition system used to read the signal from the SHT21S sensor. The computed temperature and humidity values are sent wirelessly to the access point. The end device reports periodically values each minute to the AP. The user depending on the application scenario can change this reporting periodicity value.

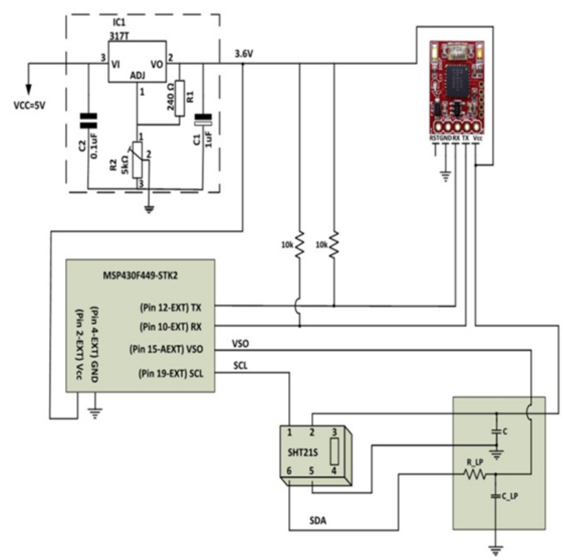

Fig. 5. SHT21S acquisition system for the standalone version.

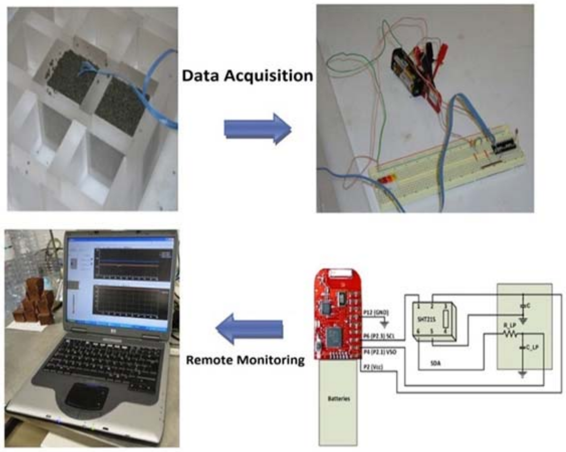

Fig. 6. SHT21S wireless acquisition system.

D. Joint Verification of Shielded SHT15 and SHT21S Sensors

The main purpose of shielding the SHT15 and SHT21S sensors is to protect the sensor from the concrete high relatively humidity alkaline environment that could affect the sensor inside the concrete. Besides, the unique capacitive sensor element used to measure humidity as well as the band-gap sensor utilized to measure the temperature do not resist to the high relative humidity alkaline environment present in cement. To overcome this limitation, in the second series of tests we have decided to use a filter cap allowing for protecting the SHT15 and SHT21S humidity and temperature sensors against dust, water immersion, condensation, as well as contamination by particles. The cavity inside the filter cap is made such that the volume between the membrane and the sensor is kept minimal, which reduces the impact on the response time for the humidity measurements. Mounting schematics of the filter cap protection for the SHT15 and SHT21S sensors is shown in Fig. 7.

4. Results and Discussion

A. Evaluation of Real-time Monitoring of Temperature and Humidity

SHM related parameters can be assessed based on the humidity and temperature values of the proposed monitoring system. As previously mentioned in the introduction section, temperature and humidity can cause damage to the bridge structure including cracking caused by temperature gradient- which itself is caused by different degrees of sunlight on different parts of the bridge-, corrosion caused by humidity and climatic factors- e.g. corrosive sea salts- and those corrosions and damages that have different origin, but in which humidity and temperature act as an accelerating factor. Assessment and comparison of temperature and humidity values with critical threshold values at different points provides the possibility of detecting present structural issues or those that are going to happen.

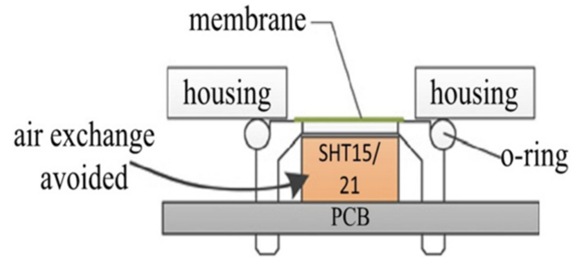

Fig. 7. Mounting schematics of the filter cap protection for the SHT15 and SHT21S sensors.

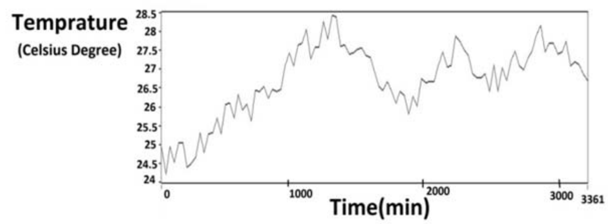

Fig. 8. Temperature data stored by wireless sensor network monitoring system and LM35 analog sensor.

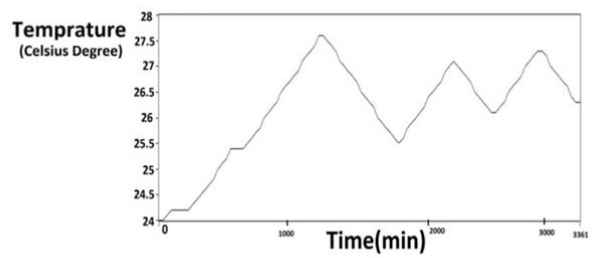

Fig. 9. Temperature data stored by wired SHT11 digital sensor.

To assess the accuracy and reliability of the proposed system, it was deployed for 3361 minutes-approximately two and a half days- to store temperature and humidity data then results were compared with the results of SHT 11 sensor which its digital temperature and humidity data was collected through a data acquisition card via wired connection. The results can be stored the databases as shown in Table 1 and Table 2. They can also be exported to the other software -like MATLAB- for further processing. Fig. 8 shows the temperature data that were stored by wireless monitoring, and Fig. 9 shows the temperature data that were stored by wired SHT11 sensor in the same period. A similar process was also used to store humidity data. Humidity data logged by wireless sensor network monitoring system and HIH400 analog sensor is shown in Fig. 10 and humidity data logged by wired SHT11 digital sensor is shown in Fig. 11. Relative error of proposed SHM system in the calculation of temperature and humidity is shown in Fig. 12.

Table 1. An example of temperature values logged in the Excel files (TEMP1, TEMP2).

Temp Reference SHT 11	TEMRATU RE VALUE	TIME	DATE
27.7	29	5.18 pm	04/14/2015
27.7	29	5.19 pm	04/14/2015
27.5	29	5.20 pm	04/14/2015
27.5	29	5.21 pm	04/14/2015
27.5	29	5.22 pm	04/14/2015
27.5	29	5.23 pm	04/14/2015
27.5	29	5.24 pm	04/14/2015
27.4	29	5.25 pm	04/14/2015
27.5	29	5.26 pm	04/14/2015
27.5	29	5.27 pm	04/14/2015
27.4	29	5.28 pm	04/14/2015
27.5	28	5.29 pm	04/14/2015
27.5	28	5.30 pm	04/14/2015

Table 2. An example of humidity values logged in the Excel files (HUM1, HUM2).

HUM Reference SHT11	HUMIDITY	TIME	DATE
35	38	5.18 pm	04/14/2015
36	38	5.19 pm	04/14/2015
36.3	37	5.20 pm	04/14/2015
36.3	36	5.21 pm	04/14/2015
36.3	39	5.22 pm	04/14/2015
36.3	37	5.23 pm	04/14/2015
36.3	38	5.24 pm	04/14/2015
36.3	39	5.25 pm	04/14/2015
36.3	38	5.26 pm	04/14/2015
36.3	38	5.27 pm	04/14/2015
36.3	37	5.28 pm	04/14/2015
36.3	36	5.29 pm	04/14/2015
36.5	38	5.30 pm	04/14/2015

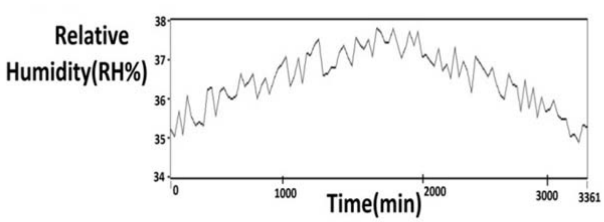

Fig. 10. Humidity data logged by wireless sensor network monitoring system and HIH400 analog sensor.

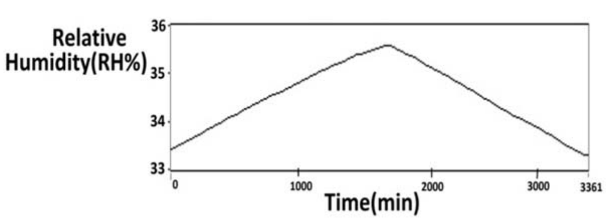

Fig. 11. Humidity data logged by wired SHT11 digital sensor.

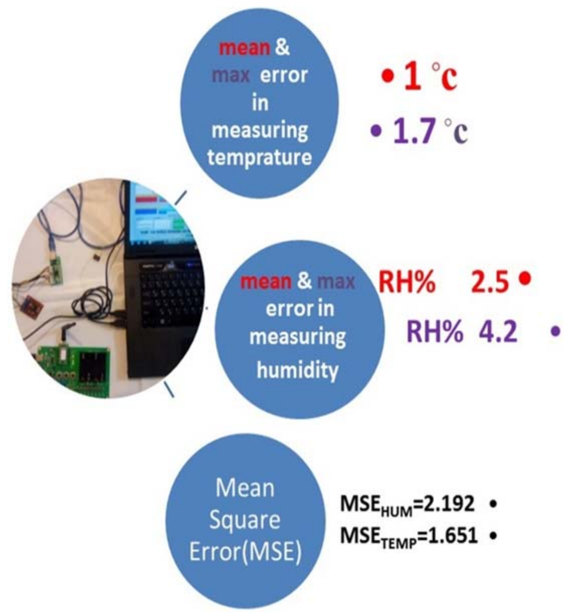

Fig. 12. Maximum error, mean error and MSE values for temperature and humidity parameters monitored by the proposed system.

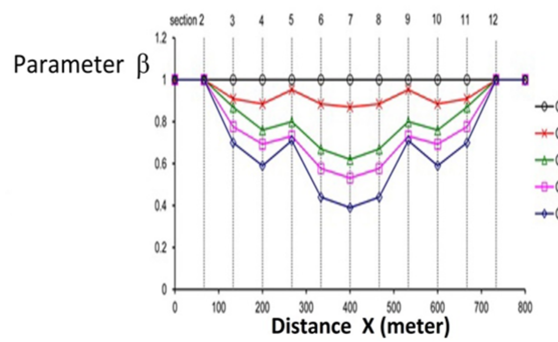

Fig. 13. β function as an indicator of the severity and location of the damage in the model structure [29].

According to assessments and the results of similar studies that were discussed in the introduction section, the thermal response of bridge structure, which is measured by the proposed SHM system, can be used to assess and evaluate the health status and structural condition of the bridge and stresses, strains and loads in the bridge structure and the reaction of its structure to these parameters. According to studies which were being mentioned in the introduction section [28]-[30] total longitudinal tensile strain (ε_T) at the height of (y) from under the arch of the bridge in one of its sections is:

$$\varepsilon_T(Y) = \varepsilon_b - \psi_b y \tag{5}$$

$$\sigma(y) = \beta E\,\varepsilon_m = \beta E\,(\varepsilon_b - \psi_b y - \varepsilon_f) \tag{6}$$

In the above equations, β is a dimensionless function of X or position along the bridge model. Values of β are in the range between zero- which indicates to the full damage and total loss of EL- and one –which indicates to the status without any damage and one hundred percent intact-. When the value of β function is known, thermal response of a damaged bridge can be estimated and calculated by Eq. (5) and Eq. (6) as shown in Fig. 13. More comprehensive information regarding the operations and calculations related to the use of the thermal response of the structure for its SHM is available in [28]-[30].

B. Negative Temperature Thermistor – Temperature Sensor

The first experimental approach for reading temperature inside a concrete cube involves the use of a negative temperature coefficient thermistor and an IRIS mote. This setup foresees an automatic wireless monitoring system. The temperatures inside the concrete cube and environment have been compared. There is a difference of 5º C between the actual and measured temperatures. This is due to some failures during the calibration of the sensor, resulting in inaccurate values. Based on this fact, we can conclude that using a NTC sensor with an ‘‘unknown’’ behavior is not the most adequate approach to the problem. Besides, this kind of sensor is not able to simultaneously measure temperature and humidity inside the concrete structures.

C. SHT15 Humidity and Temperature Sensor

The second set of tests considers the use of the SHT15 sensor, allowing for measuring both the humidity and temperature. Two solutions were tested, one with the PIC18F4680 microcontroller and another one using the Arduino platform. Before using the SHT15 sensor in a real scenario, some tests have been performed to verify the accuracy of the temperature and humidity readings. To measure humidity we place the SHT15 sensor inside a small mortar cube for sensor protection. When the cubes were placed in a tray (with 2–3 mm water level), we observed the rise of water inside the cube by capillary. After around one minute, the humidity reaches a value of 98% RH. The objective of this test was to verify the sensor integrity, as well as the porosity effect of its mortar shell. The results obtained from both PIC18F4680 and Arduino platform were identical. The tests were carried out during several hours, to observe if any variation of humidity and temperature could be detected.

In another experiment a SHT15 sensor with a mortar shell was fully immersed in water. One observes that the temperature was decreasing while the humidity was increasing. After 20 min of accurate measurements, we have decided to prolong the test during one week. However, after one day, the SHT15 temperature sensor went off. Then, after 4 days the same happened to the humidity sensor. It is believed that the primary reason for this occurrence is that some chemical reactions inside the mortar shell have affected the capacitance of the sensor. Sensor components might not resist to alkaline ions present in cement, namely calcium hydroxide, which can be released in water from its mortar shell during immersion. To solve this problem, instead of making a cement-based mortar shell it may be preferable to shield the sensor using other material, textile or polymer based.

D. SHT21S Humidity and Temperature Sensor

1) Standalone Version

The SHT21S sensor protected by a mortar cube was placed inside a concrete cube during testing. The values measured by the sensor were recorded into the micro SD card. The measurements were performed in outdoor environmental conditions during summer. During the first 12 h there has been a constant and progressive variation; while between the 12th and 16th hours a decrease in the temperature and humidity values has been observed. After 16 h, the sensor stopped reading the temperature values. Only the humidity values have been measured beyond this time instant. As occurred with SHT15, the SHT21S sensor components have not resisted long time inside the concrete alkaline environment. To overcome this limitation, shielding of sensor is also advised in this case, e.g., with textile, polymer Poly-Butylene-Terephthalate or even metal shielding.

2) Wireless Version

In scenarios of remote monitoring, there is a need of extracting and recording the data gathered by the sensor nodes. To avoid the need of regularly visiting, remote access to the collected data is essential. Moreover, solutions involving WSNs have a tremendous potential in real time structural health monitoring, since they potentially reduce costs.

The SHT21S wireless version allows for collecting the information from any given structure via the SHT21S eZ430-RF2500 C++ software program which is responsible for the acquisition of the values from the SHT21S sensor. To analyze the acquired values we can export the data to a MATLAB-file. The results obtained for temperature and humidity are quite accurate. Therefore, the use of a porous cement mortar as protective shell does not affect the sensor readings. This method of protection of the sensor is similar to those developed by [27] which is recently published, although unknown to authors during the experimental phase. However, the presented solution does not consider an encapsulation box for the electronic acquisition system components -since it is outside the ‘‘brick’’-. This way we are able to obtain more accurately values for the temperature and humidity since the sensor is placed as close to the environment as possible. By using an encapsulation box the detected temperature and humidity may not be the actual structure temperature and humidity, as stated in [28]. Besides, in the work developed by [27] the Radio Frequency Integrated Circuit (RFIC) transmitter is inside the brick, being the maximum effective reception range bellow 20 m.

The research also considers a package to protect the sensor from the aggressive environment. Preliminary results show that the transmission distance is strongly affected by the steel backed formwork, showing that the maximum distance achieved without the formwork is 7.5 m. In our case, by considering the open field scenario -since the acquisition systems is outside the ‘‘brick’’- the eZ430-RF2500 can achieve a minimum effective reception range of 35 m. In this experiment, the SHT21S sensor temperature readings have been successfully performed during the first 16 h, while the humidity values were successfully obtained during the first 21 h. After this period, the sensor went off which is possibly caused by the alkaline concrete environment that stopped the sensor operation.

E. Joint Verification of Shielded SHT15 and SHT21S Sensors

In this set of experiments, the SHT15 and SHT21S sensors, which are previously shielded, were inserted into two small mortar cubes -4 cm of side length- before being inserted into the concrete block. To test the accuracy of the measurements, the mortar cubes were first placed in a tray with water. After some time, we observed the rise of water inside the cube by capillarity. Then, the cubes were removed for drying. As is shown in Fig. 14, the cube containing the SHT15 sensor initiated the drying process after 10 h, while the cube containing the SHT21S sensor started the drying process after 60 h. After 97 h, we have repeated the test of placing the cubes in a tray with water, in order to observe the increase of the humidity values.

The standard deviation between the humidity values, which are measured by the SHT15 sensor and the SHT21 sensor, is explained by the fact that the small cubes are not exactly the same, so some variations in terms of humidity may exist during the drying process. Also, if the SHT21S is exposed to conditions outside the normal operation range (humidity > 80%), an offset could exist. Therefore, in high relative humidity environment it is advised to use the SHT15 sensor. The measured temperature is similar to the ambient temperature. As can be seen in circle 1 in Fig. 14 in the first 20 hours of testing, both SHT15 sensor and SHT21s sensor measure the temperature carefully with appropriate adaptation in response to the changes in ambient temperature, but in almost 22th hours of the start of the experiment, both of them sense a sharp drop in temperature. With increase of ambient temperature, they measure high temperatures in steady state which represents the appropriate sensitivity in the application of structural health monitoring of concrete structures. On the other hand, this represents the stability and performance of both sensors within the first 25 hours of test.

Regarding to the circle 2 in Fig. 14, it should be considered at the same constant ambient temperature, both sensors reported about 0.5 ° C temperature swings that the interpretation of which can be differences in the type of cement cube which is used to protect them. The cubes are not exactly in the same structure and geometry so some differences and swings occur in the above mentioned range in respect to the reference temperature. Regarding to the circles 3 and 4 in Fig. 14, there are similar explanation about measuring of the temperature which have been described before. They implicitly refer to the failure of protecting shielded system using concrete cubes which caused some inertia and errors in temperature measurements by both of above mentioned sensors.

Regarding to the circle 5 in Fig. 14, after starting the drying process, the reference sensor is broken but SHT15 and SHT21s sensors continue to operate. This indicates the following two points:

- Capability of both sensors to measure temperature within or adjacent concrete.
- High performance of the proposed protection system including concrete cubes.

Regarding to the rectangle 6 in Fig. 14, as previously mentioned, it should be pointed out about the lack of proper functioning of the SHT21s humidity sensor in the first 60th hours of the test which is in the saturated conditions. This part of the test is reached us to the following conclusions:

- Non-performance of the protection system, including concrete cubes for protection of humidity sensor SHT21s.
- The usage of the humidity sensor SHT15 in SHM applications at environments with high moisture (more than 90%), is preferable.
- In the final step of this study, the SHT15 and SHT21S sensors, which were previously shielded and protected by a mortar cube, were placed inside a concrete cube during the test. The values measured by the sensors were recorded into the micro SD card. The data collected from the sensors is shown in Fig. 15. The tests

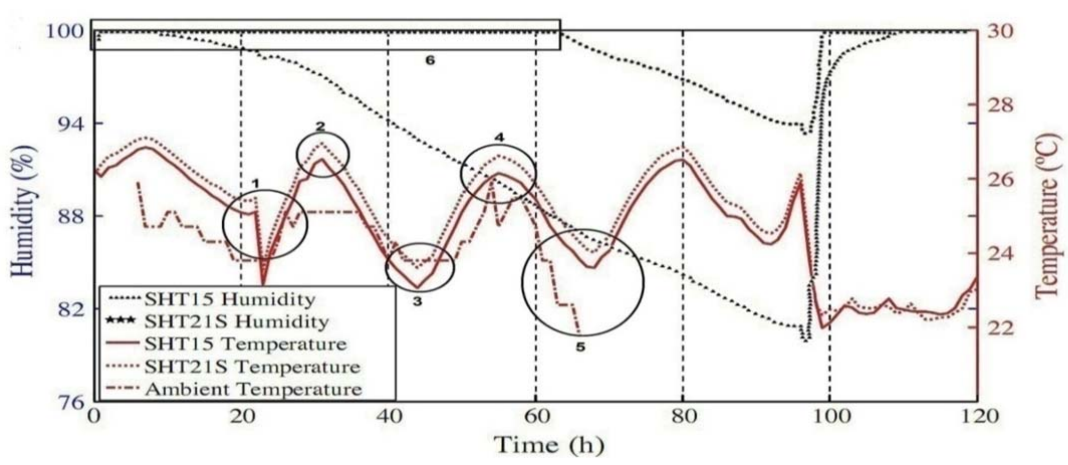

Fig. 14. Results for the humidity and temperature obtained using the SHT15 and SHT21S sensors during 5 days.

were performed during 6 days. During the first 12 h, there is an increase of the humidity for the cube containing the SHT15 sensor, while the humidity inside the cube containing the SHT21S sensor achieves the maximum value (i.e., 100%). During the curing process, the temperature inside the cubes was about 37 ˚C after the first 11 h. Therefore, we may conclude that by using a filter cap as shown in Fig. 7, we protect the humidity and temperature sensors and a long-term solution for SHM is obtained. This is one of the major goals in this study. Finally, it was verified that both sensors were performing measurements inside the concrete after 2 months of experiments.

In fact Fig. 15 is laboratory-controlled version of the early stages of the formation of concrete and hydration process. Circle 1 in Fig. 15 represents the initial phase of the formation of concrete where the temperature has gone up- which is induced by rapid hydration rate- while high level of humidity still remains. Under these conditions, both temperature and humidity sensors SHT15 and SHT21s have good performances. After the initial phase of hydration, by reducing the temperature and humidity during a process which is known as “drying”, SHT21s remains in the saturated condition but SHT15 moisture sensors continues to measure the humidity well. This demonstrates the capabilities of SHT15 in the real-time & continuous measurements of humidity in the vicinity of severe alkaline environment of concrete. On the other hand, by comparison of the SHT15 results with reference sensor results, we found that organic material protection system does not affect the accuracy and sensitivity of the SHT15. It helps SHT15 for withstanding and measuring of the temperature and humidity with high acceptable accuracy which is shown in the area inside the circle 3 in Fig. 15.

Throughout the mentioned period, both sensors measure the temperature with reasonable accuracy. This is the evidence of this fact that the shielding protection system has not any bad effects on the accuracy of the temperature measurements. It Increases the lifespan of temperature sensors via shielding organic materials.

In the Circle 3 in Fig. 15, it can be seen some differences in the results of temperature sensors SHT15 and SHT21s. The reason of those differences, as we have already mentioned, is that the two sensors did not exposure on equal conditions within the desiccator. Another reason is the dissimilarity in the types of the shielding which are not 100% equal and have slightly different properties.

Regarding to the rectangle 4 in Fig. 15, during all of this period, humidity sensor SHT21s is in saturation mode and does not show an appropriate performance in measuring of the humidity in the presence of an alkaline environment in the concrete. On the other hand, this behavior reflects the inefficiency of the proposed shielding protection system in the protection of the humidity sensor SHT21s.

As a summary of Fig. 15, which is in fact a controlled-laboratory conditions to investigate the processes of hydration and the initial formation of the concrete, it should be noted that the system including a sensor SHT15 and proposed shielding protection system (as stated before in section 3.4), has an acceptable functionality which is required for being used in SHM of the concrete structures.

5. Conclusion

In this study, a system with multiple functions for monitoring the structural health of a medium sized assumed bridge with the use of wireless sensor networks was designed, implemented, and simulated. The proposed SHM system monitors the parameters of temperature and humidity in two points of the bridge deck. A wireless sensor network has been created based on the IEEE 802.15.4, allowing for the creation of a continuous monitoring system capable of sending data wirelessly. In this network, the nodes used two types of sensors, the SHT15 and SHT21S ones, to read both humidity and temperature, in real-time and continuous monitoring basis. The obtained results show two types of sensors and the measurement procedure have highly potential for inexpensive concrete structure monitoring. However, during the first set of experiments the SHT15 temperature

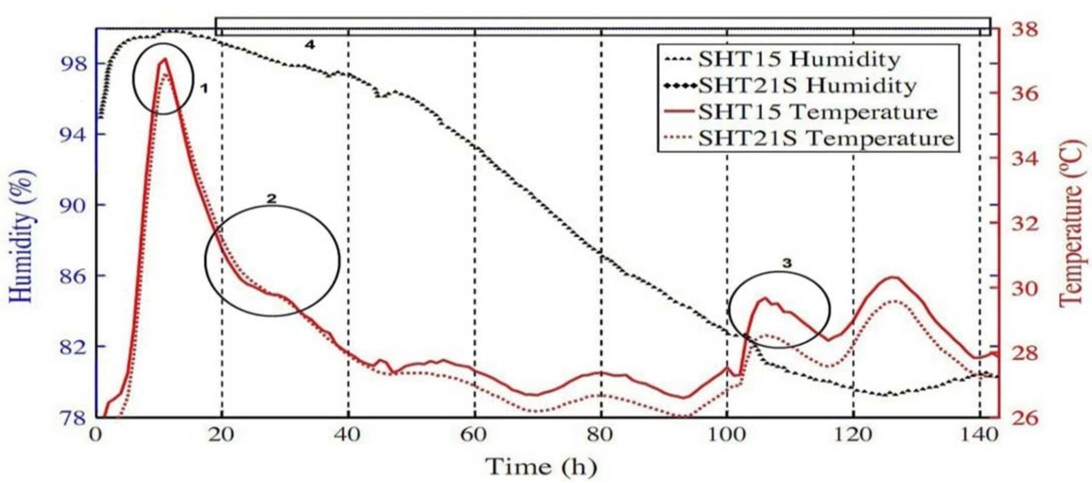

Fig. 15. Results for the humidity and temperature obtained using the SHT15 and SHT21S sensors inside a mortar shell for 143 h.

sensor stopped working after one day. Besides, after four days, the same happened to the humidity sensor. The temperature readings from the SHT21S sensor have been successfully performed during the first 16 h of the experiment, while the humidity values were successfully obtained for the first 21 h. After this period the sensor went off. The initial sets of results were very promising, although SHT15 and SHT21S sensors went off after some time inside concrete. This is explained by the fact that the components of the sensors do not resist to concrete high relative humidity alkaline environment.

The experiments carried on also shown that a porous cement mortar could be used as shell to protect sensor wire connections. High porosity of this mortar shell easily allows moisture and temperature measures of involving concrete but this solution does not protect sensors of the alkaline environment. Hence, it is advised to shield the sensors before using them within the structure, especially during the construction phase. It is also advised to use sensors that can resist in concrete alkaline environment.

In the end, given the accuracy and reliability of assessments and analysis results and the much lower costs of this system in terms of initial equipment and maintenance (due to the simplicity of its structure) proposed SHM system can be used for the long-term and real-time monitoring of medium-sized to large-sized reinforced concrete bridges.

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