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A New Inexpensive System for SHM of Bridge Decks Using Wireless Sensor Networks Based On Measurements of Temperature and Humidity

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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, and then it was implemented and investigated. A scaled model of a conventional medium sized bridge (length of 50 meters, height of 10 meters, and with 2 piers) was examined for the purpose of this study. This method includes installing two sensor nodes with the ability of measuring temperature and humidity on both side of the bridge deck. The data collected by the system including temperature and humidity values are received by a LABVIEW-based software to be analyzed and stored in a database. Proposed SHM monitoring system is equipped by a novel method of using data mining techniques on the database of climatic conditions of past few years related to the location of the bridge to predict the occurrence and severity of future damages. In addition, this system has several alarm levels which are based on analysis of bridge conditions with fuzzy inference method, so it can issue proactive and precise warnings and alarms in terms of place of occurrence and severity of possible damages in the bridge deck to ensure total productive (TPM) and proactive maintenance. Very low costs, increased efficiency of the bridge service, and reduced maintenance costs makes this SHM system a practical and applicable system. The data and results related to all mentioned subjects were thoroughly discussed and the accuracy and reliability of the SHM systems were evaluated. The results show that this system is qualified to be used as a SHM system in medium to large bridges.

Keywords: *Structural Health Monitoring, Wireless sensor networks, Proactive Maintenance of Bridges, Data mining and fuzzy inference techniques.*

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 damage caused by the temperature gradient, cracking, fatigue, corrosion of structures and the decrease of load capacity of the bridge, etc. which 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 [1-3] 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

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bridge such as shifts in frequencies of pier and changes in the modes of vibration and assessing the structural damping index or modal assurance criterion, etc. The characteristics of low-frequency pier vibrations are not sensitive to small damages and changes in structure, so monitoring systems have to cover higher frequencies to detect such changes [4] and this necessarily requires a significant number of highly sensitive transducers and also data acquisition system with a high rate of sampling [5]. It also requires a complex procedure of data processing for the detection of changes in the dynamic characteristics of the structure. In addition, changes in natural frequencies that are caused by structural damage can be easily overlooked under the influence of environmental effects, especially changes in temperature and humidity [6-9].

The presence of these difficulties and limitations [10-16] is the main motivation for the investigation of other SHM methods for bridges. 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 it has been analyzed with the help of a hypothetical bridge. Researcher claims that this method has the ability to bypass the mentioned problems and limitations. 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 [7, 8, 9]. 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 [10]. 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 prestressed concrete bridges, thermally induced stresses are usually in the same range of live load stresses but are often greater than these stresses [11]. Slow and wide-range changes facilitate the use of thermal response methods such as measuring the temperature in different parts of the bridge which can be easily monitored. This monitoring can be easily performed through conventional and inexpensive transducers and data acquisitions systems which have low sampling rate and can simultaneously monitor the environmental heat loads and the responses of the bridge. The condition of bridge structure (especially the metal sections) can also be monitored for the effects of humidity, so timely measures can be taken based on these data to improve its condition. Such SHM system provides large amounts of valuable data than can be used to perform calculations in a comprehensive manned and on a daily basis. In addition, the thermal responses are semi-static, so required analyses are less complex than the dynamic behavior. On a sunny day, the temperature of the surface of the bridge deck is much higher than the temperature of the underside of the deck, and this causes the bridge flexure to be drawn upward. For a typical curved bridge, this phenomenon has little effect on the reaction of pier section or internal forces such as stresses or strains.

On the other hand, for a continuous bridge with several curves, this phenomenon changes the reaction of piers and cause thermally induced momentary stresses and strains along bridge flexure. These thermally induced responses are a function of EL. Therefore, the cracks and damages in curved sections of the bridge can substantially alter the effective EL of the bridge have considerable effects on these response [10] and [11]. 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 prestressed 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 severity like previous common methods. [12, 13].

The second section of this article introduces the details of proposed SHM system and its implementation, the hardware and configuration of sensor network, and designed monitoring program and then discusses the manner of improving the proposed method to a proactive system with the ability to predict the temperature and humidity. The third section assesses and evaluates the results of proposed SHM, average and maximum error, and the mean squared error whether in measurement stage or in the process of predicting the temperature and humidity. That section also assesses the details of a warning system based on fuzzy inference. The final part of the third section presents some examples of practical applications of the proposed monitoring system in the maintenance procedures of conventional bridges. The fourth section summarizes the discussed issues and the advantage and disadvantages of the method.

2. PROPOSED SHM SYSTEM AND ITS HARDWARE, SOFTWARE, AND IMPLEMENTATION

2.1 Description of proposed SHM system and its components and principles

In this paper, a SHM system with the following characteristics was designed, implemented, and simulated for a hypothetical bridge:

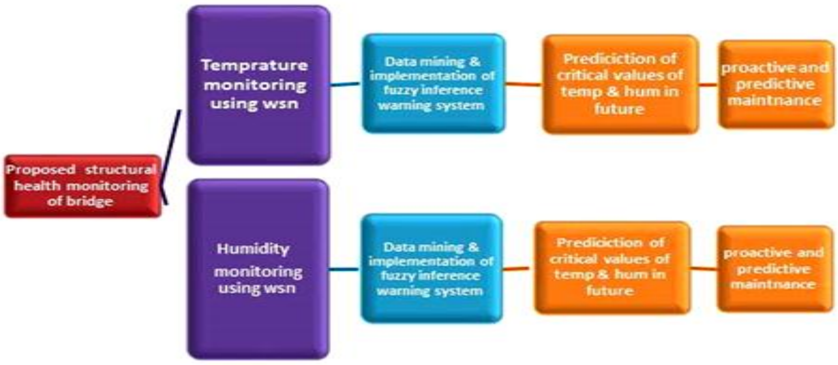

Figure 1: an Overview of the proposed SHM systems and its components and function

As shown Figure 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 repair and maintenance team.

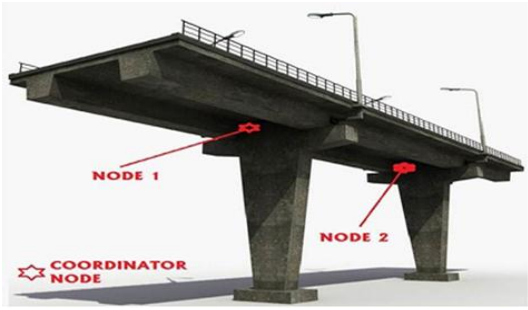

Figure 2: SHM systems of the presumed bridge and layout of its components

2.2 Description of hardware and wireless sensor nodes for monitoring temperature and humidity

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 (as shown in Figure 2). 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 and Figures 3 and 4 shows the layout of used PCB. 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 (Figure 5).

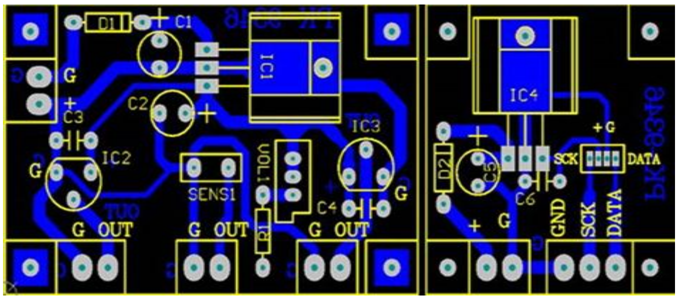

Figure 3: layout of PCB of board and bias circuits of temperature and humidity sensors

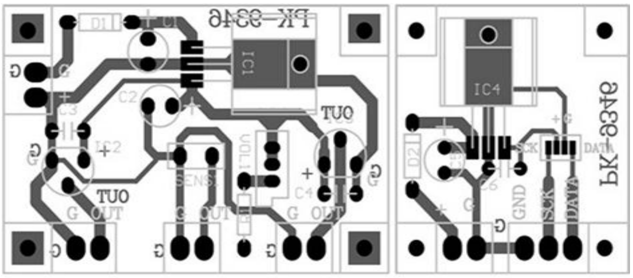

Figure 4: PCB of circuit

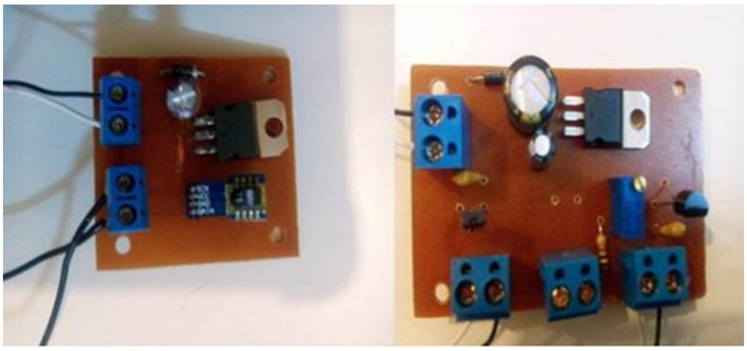

Figure 5: The final layout of sensor nodes (Analog nodes including LM35 and HIH4000 sensors on the right, and SHT node on the left)

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. The image of this module and its development board can be seen in the Figure 6 and Figure7respectively.

Figure 6: the Image of ZE10 module

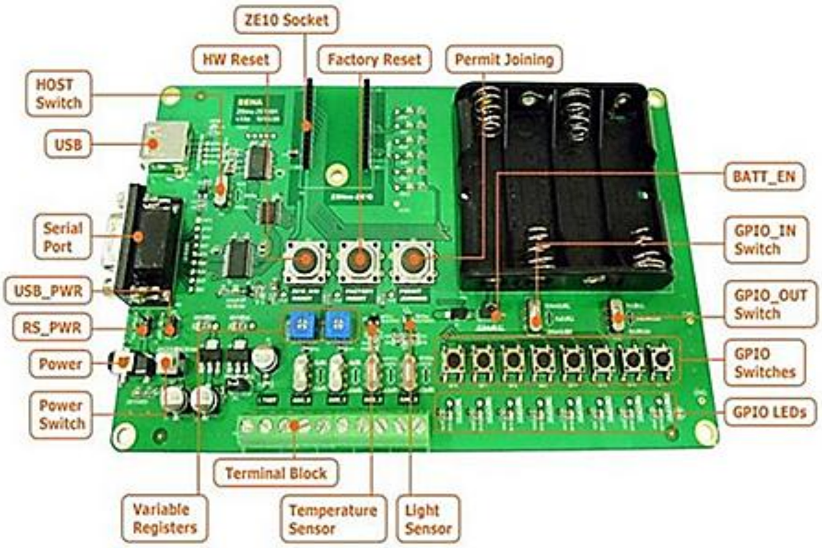

Figure 7: the Image of ZE10 development board

In the next step, 3 selected wireless modules were configured. 2 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. These settings are also available through the proBee manager software and the Figure 8 shows a view of this software.

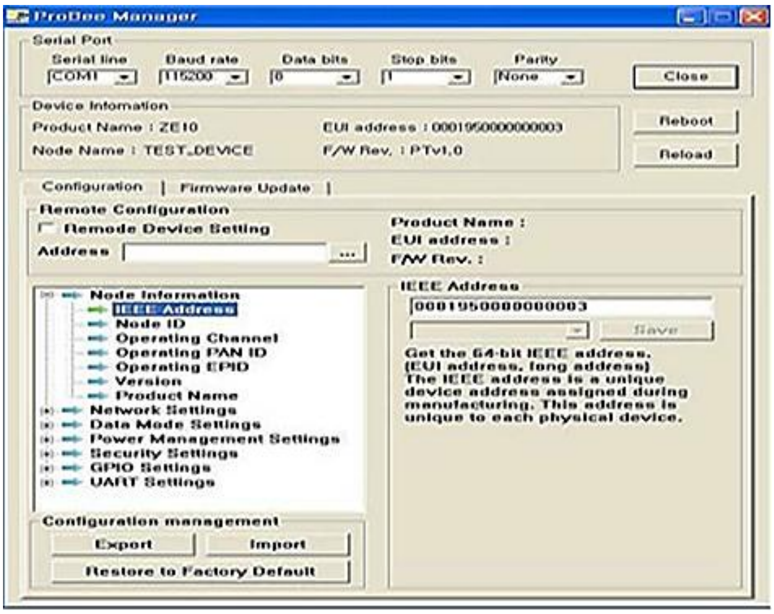

Figure 8: proBee manager software

There are 4 analog to digital channels in the final module, and their configuration was performed through the software in a way that channels 0 and 1 were dedicated to potentiometers in the development board for initial and required tests of the program, and channels 2 and 3 were dedicated to connecting the output of temperature and humidity sensor in each node respectively. After performing the initial configuration of all nodes and connecting the sensors and feeds of all three nodes, the sensor network will have the Figure 9 overall configuration.

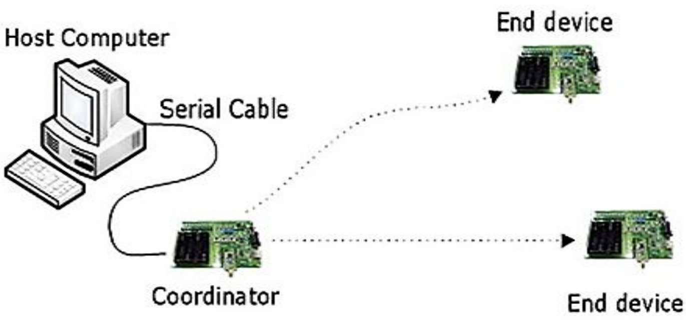

Figure 9: Overall configuration of wireless sensor network used in SHM system

2.3 Description of application software used for monitoring the temperature and humidity

In the coordinator node connected to a computer through a USB port, values related to analog channels 3 and 4 (the temperature and humidity) in each node can be read and received through the following command:

In case of our nodes, MAC addresses were as follows:
NODE 1 MAC ADDRESS: 00019500000003a
NODE 2 MAC ADDRESS: 000195000000014

After sending the above data string in Labview software program, a series of 32-bit hexadecimal values sampled from 4 analog channels of node 1 and node 2 will be sent to coordinator node (with about 2 to 3 seconds delay) , and then will be entered into software through serial port. The Labview software will perform the processes of retrieving and separating data strings and converting hexadecimal data to decimal, and then applies calibration coefficients to obtain correct values for temperature and humidity, and then displays these values while also saving them in Excel format in separate files with the date and time of data recording. These files include “hum1” and “temp1” for the node 1 and “hum2” and “temp2” for the node 2.Figure 10 shows further details of front panel of this software.

Figure 10: Front panel of software

In this panel, all received values and data strings and all operations which are performed on them at each step can be easily reviewed by user through String indicator. It also plots a graph for temperature and humidity at each node, and a graphical barometer separately shows the accuracy of system performance. Values that are stored in Excel files are also displayed in this application. The main parts of temperature and humidity monitoring application (in node1 for example) and SHT11 sensor data acquisition application are shown in the following figures. (Figures 11 and 12 and 13 and 14)

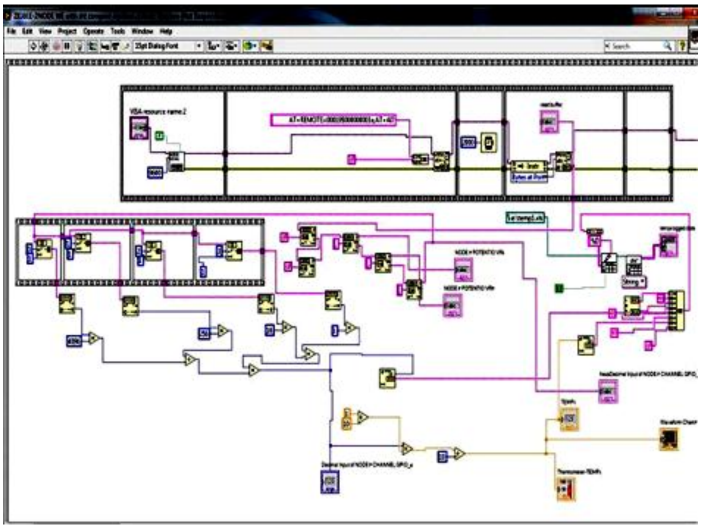

Figure 11: wireless temperature measurement application for node 1

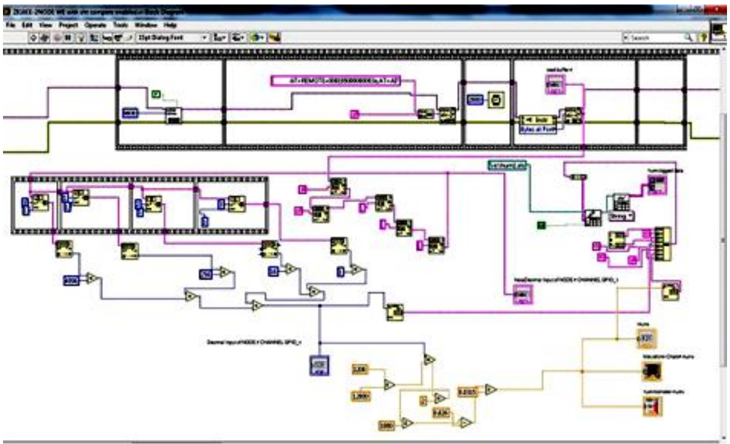

Figure 12: wireless humidity measurement application for node 1

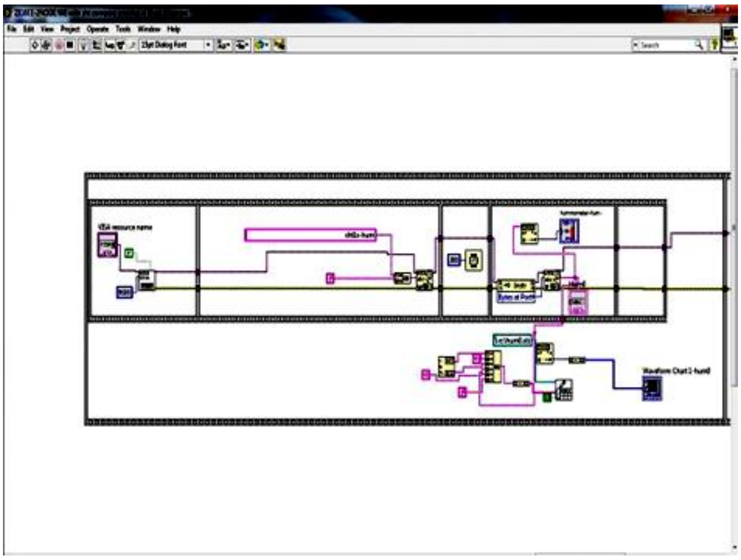

Figure 13: SHT11 sensor data acquisition application (for temperature)

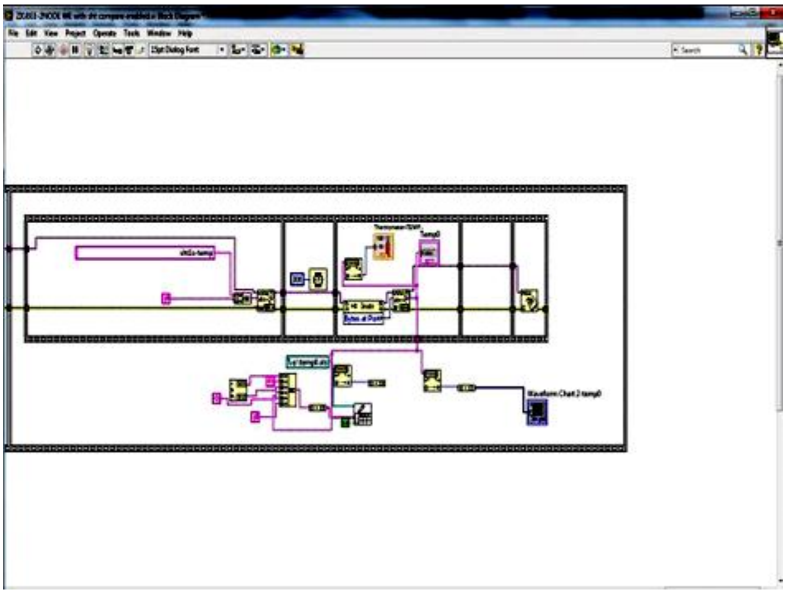

Figure 14: SHT11 sensor data acquisition application (for humidity)

2.4 Implementation of temperature and humidity monitoring system

The Figure 15 and Figure 16 show the images of end nodes, sensor connections, and coordinator node (Figure 17) connected to a computer. The image of USB DAQ used for acquiring data from SHT sensors is also presented (Figure 18).

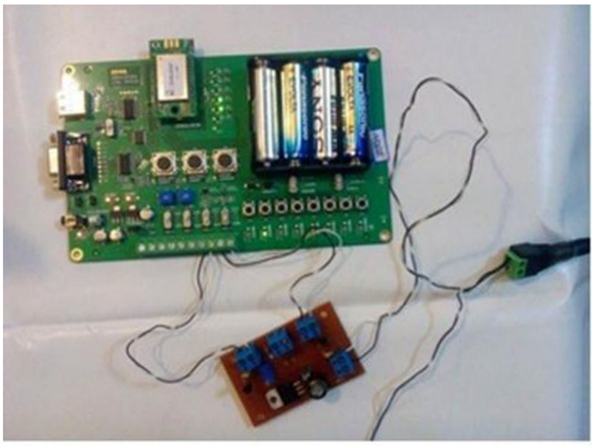

Figure 15: Node 2 (end node)

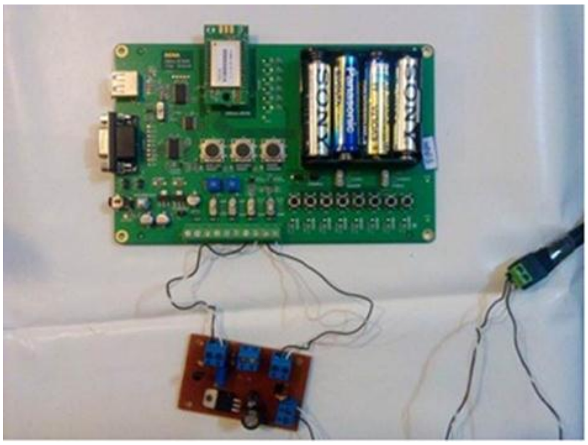

Figure 16: Node 3 (end node)

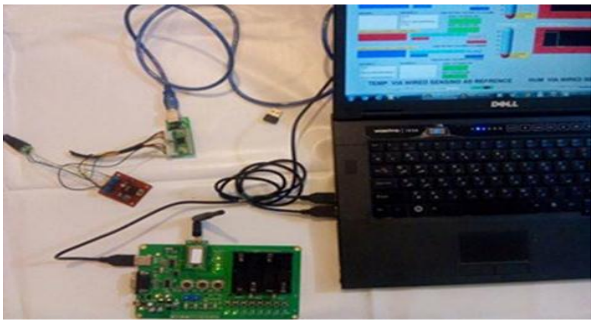

Figure 17: The mother node (COORDINATOR) + PC

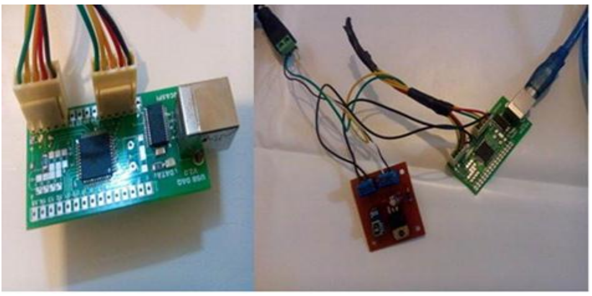

Figure 18: SHT11 digital sensor board + USB DAQ

2.5 Upgrading the proposed method to a proactive system capable of predicting temperature and humidity

After the formation of temperature and humidity monitoring system mentioned above, a novel method was used to predict the temperature and humidity in the nodes for the following days (according to the database of the weather condition in the past 4 years in the area where the bridge is located). Details of this method are as follows.

The Basis of this method is to use temperature and humidity data for the past 4 years (which are collected in a database (Figure 19) and are sorted based on different months) and the temperature and humidity of last 3 days recorded on “hum1” and “temp1” files for node 1 and “hum2” and “temp2” for node 2, and also utilize MATLAB software and a data mining technique called K-Nearest Neighbour, to predict the temperature and humidity for the desired date. If the values of this predicted data exceed the limits (alert level) determined by Fuzzy techniques, system will notify the maintenance personnel to perform proactive or predictive maintenance and repair procedures on the bridge. A graphical interface was designed for user convenience which its details will be discussed in the third section of paper. This GUI provides the possibility of comparing and validating the predictions and values by numerical and graphical means. In fact, adding the ability of predicting the temperature and humidity conditions in the following days has upgraded the proposed SHM system from a simple monitoring system to an Ideal system for bridge maintenance.

2009	Temp. (°C)			Dew Point (°C)			Humidity (%)			Sea Level Press. (hPa)			Visibility (km)			Wind (km/h)			
Mar	high	avg	low	high	avg	low	high	avg	low	high	avg	low	high	avg	low	high	avg	high	
1	38	30	22	9	7	4	35	25	14	1014	1011	1009	6	6	6	42	5	-	
2	40	29	19	10	7	4	52	27	11	1014	1011	1008	6	6	3	21	3		27
3	40	30	21	10	8	5	46	24	12	1013	1010	1008	6	6	5	11	2	-	
4	40	32	24	12	7	3	44	24	11	1013	1010	1007	6	6	6	19	3	-	
5	41	32	24	12	4	2	27	19	9	1012	1009	1006	6	6	5	27	8	-	
6	39	31	23	7	5	2	33	21	10	1013	1010	1008	6	5	5	19	6	-	
7	39	31	23	10	4	1	44	20	11	1014	1010	1007	8	5	2	14	5	-	
8	40	30	21	10	6	3	40	24	11	1012	1009	1006	6	5	3	11	2	-	
9	38	30	22	14	12	7	44	32	21	1013	1010	1008	6	5	4	19	3	-	
10	38	31	25	12	9	7	41	28	18	1016	1013	1011	6	5	0	14	6	-	

Figure 19: Database (sorted in the Excel file)

On the other hand, the average amount of humidity and temperature in the last 3 days is recorded by monitoring system in “hum1” and “temp1” files for node 1 and “hum2” and “temp2” for node 2. This data set is called “query”. The overall layout of the above technique to predict the temperature and humidity is presented in the following figure 20.

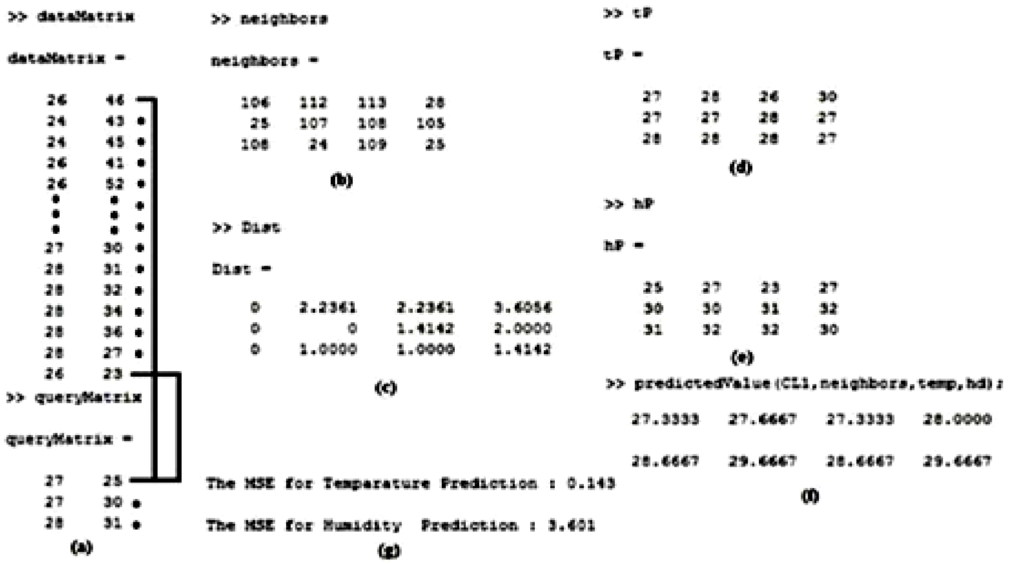

Figure 20: The overall layout of the Nearest Neighbour algorithm.

Section 16(a) of the above Figure 16 shows Data Matrix and Query Matrix. The first matrix includes the average values of temperature and humidity in the same month during the last 4 years. For example if the target date is 28-2-2015, Data Matrix will include the humidity and temperature values for February 2011, 2012, 2013, and 2014 and it will be a matrix.

Query Matrix includes the temperature and humidity values of the last 3 days leading to target date. So for the above example, it will include the data for 25-2-2015 ،26-2-2015 ،and 27-2-2015. KNN algorithm calculates the 4 nearest neighbors for the humidity and temperature values of each day in the Query Matrix, and stores them in “Neighbours Matrix” (as shown in Figure 16(b)). The Euclidean distance of elements of mentioned matrix will be stored in “Dist Matrix” (Figure 16(c)). Rows of this matrix indicate the i-th day of Query Matrix, and its i-th column indicate the i-th closest neighbor for humidity and temperature values on the i-th day. Sections of figure 16(c) and 16(d) show the humidity and temperature values of Data Matrix for parameters obtained from the Neighbours Matrix. The Average of values of i-th column of tp and hp matrices will be the predicted values for temperature and humidity in the i-th day. Figure 16(e) shows the predicted values for the target date and its four following days (28-2-2015 to 2-3-2015 for the mentioned example).For similar examples please refer [22-24].

3. EVALUATION OF PROPOSED SHM

3.1 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 (itself caused by different degrees of sunlight on different parts of the bridge), corrosion caused by humidity and climatic factors (corrosive sea salts), and those corrosion and damage that have different origin, but in which humidity and temperature act as an accelerating factor. In this section, short-term measured data and graphs of proposed monitoring system for two points is presented in Tables 1 and Table2 and Figure 21. 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).

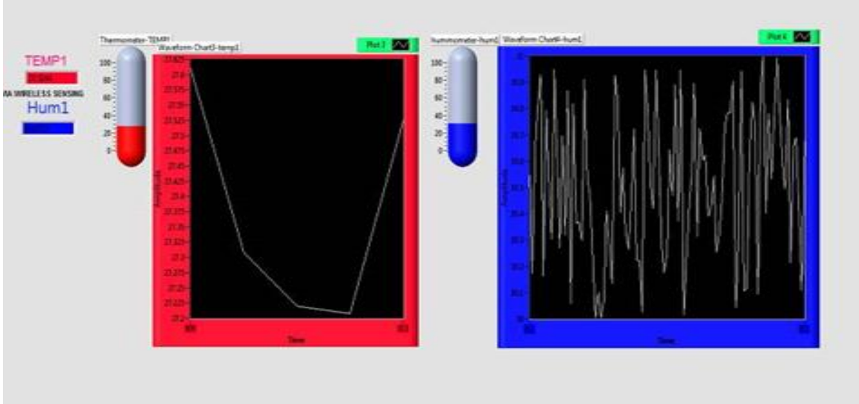

Figure 21: Humidity and temperature graphs of proposed SHM system

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

Temp reference SHT 11	TEMRATURE 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 REFFRENCE 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

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, and 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. Figure 22 shows the temperature data that were stored by wireless monitoring, and Figure 23 the temperature data that were stored by wired SHT11 sensor in the same period.

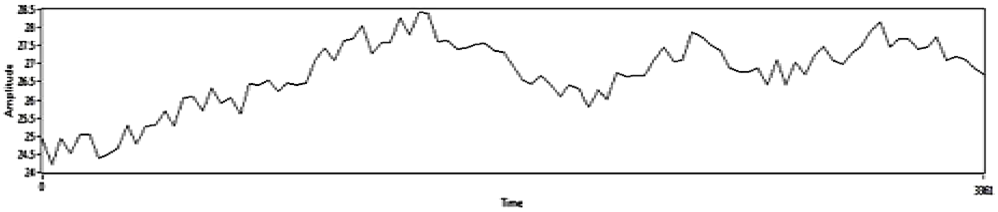

Figure 22: Temperature data stored by wireless sensor network monitoring system and LM35 analog sensor

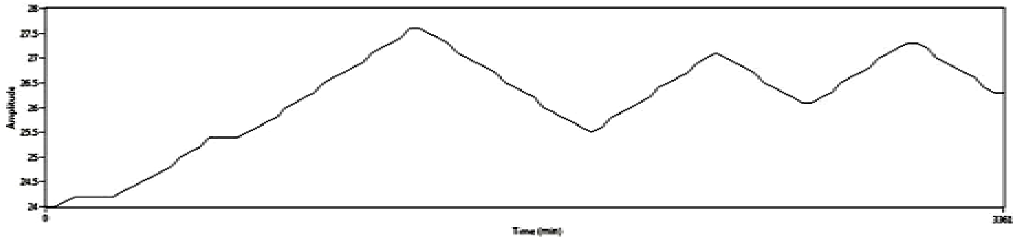

Figure 23: Temperature data stored by wired SHT11 digital sensor

A similar process was also used to store humidity data, and the results are as follows in Figure 24 and Figure 25.

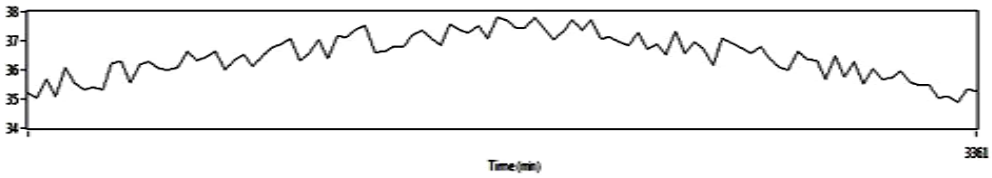

Figure 24: Humidity data logged by wireless sensor network monitoring system and HIH400 analog sensor

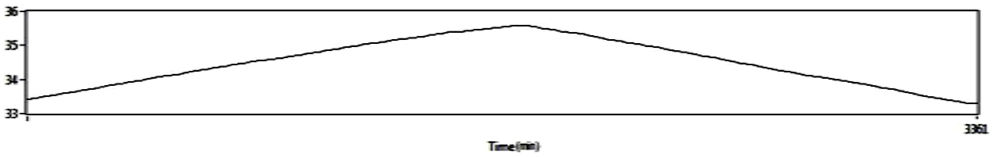

Figure 25: Humidity data logged by wired SHT11 digital sensor

Relative error of proposed SHM system in the calculation of temperature and humidity is as Figure 26.

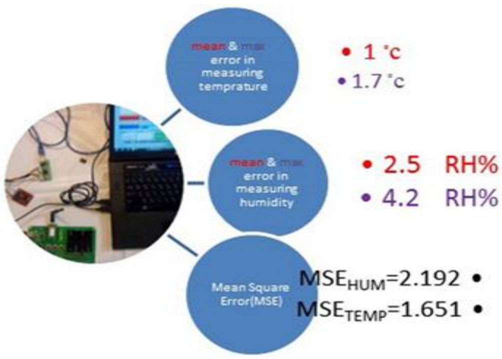

Figure 26: Maximum error, mean error and MSE values for temperature and humidity parameters monitored by the proposed system

According to assessments and the results of similar studies that were discussed in the introduction section, the thermal response of bridge structure (that 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 structure and the reaction of structure to these elements. According to studies mentioned in the introduction section [14, 15, 16], total longitudinal tensile strain (ε_T) at the height of (y) from under the arch of the bridge in one of its sections is:

$$\varepsilon_T(Y) = \varepsilon_b - \psi_b y \tag{1}$$

where ε_b is the total longitudinal tensile strain at the height of arch of the bridge, in other words $\varepsilon_b = \varepsilon_T(0)$, and ψ_b is the amount of curvature in the section that we have chosen for calculation.

The difference between ε_T and ε_f (thermal tensile strain) equals ε_m (mechanical strain) which means:

$$\varepsilon_m = \varepsilon_T - \varepsilon_f \tag{2}$$

In the end, the mechanical stress at point y that is shown by is equal to:

$$\sigma(y) = E\,\varepsilon_m = E(\varepsilon_T - \varepsilon_f) \tag{3}$$

where E is the modulus of elasticity of the material (concrete in this case). On the other hand, according to the results of model proposed and proved in [14,15,16], we have:

$$\sigma(y) = \beta E\,\varepsilon_m = \beta E(\varepsilon_b - \psi_b y - \varepsilon_f) \tag{4}$$

In the above equation, β is a dimensionless function of X. values of β are in the range between zero (full damage and total loss of EL) and one (without 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 equation (3). But in this study we want to determine β. Determination of β through matching and assessing the predicted values [14,15,16] and thermal response of the damaged bridge (obtained from the proposed monitoring system) will enable us to identify and map the distribution and severity of damages (fractures and wave-form cracks) in the bridge.

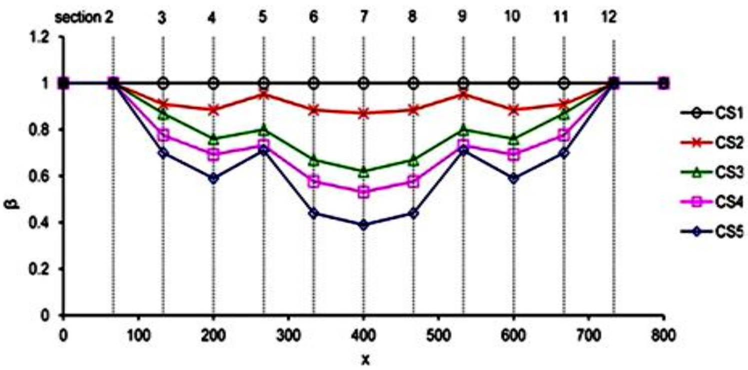

Figure 27: β function as an indicator of the severity and location of the damage in the model structure [15]

The mentioned idea is the bases of proposed method to detect damages in structures by using the thermal response of structures [14,15,16]. As can be seen in Figure 7-c, β function shows the extent of damage of wave-form fractures in the model bridge mentioned in [14,15,16] proportional to the levels of damage of CS1, CS2, CS3, CS4, CS5, which increase in that order. On the other hand, structure's thermal response and profile will be determined through proposed WSN-based SHM system. More comprehensive information regarding the operations and calculations related to the preparation and use of the thermal response of the structure is available in [14-15].For similar research please refer to [17-21].

Overall, $\varepsilon_T, \varepsilon_f$ parameters in Eq. (3) will be determined by thermal response monitored by the system, and then $\sigma(y)$ (mechanical stress) will be calculated at each y, and in the end once all parameters are determined β will be obtained.

3.2 Evaluation of the prediction of temperature and humidity values based on data mining and fuzzy inference

A graphical user interface or GUI was designed to facilitate data entry and display of outputs for the section of application that predicts the temperature and humidity to prevent the spread of the damage and to guarantee predictive and proactive maintenance and repair. This GUI was designed by C# software, and about 700 lines of code were added to link the tags to the main program of KNN algorithm. An overview of the designed GUI and description of different parts this GUI is presented in the Figure 28.

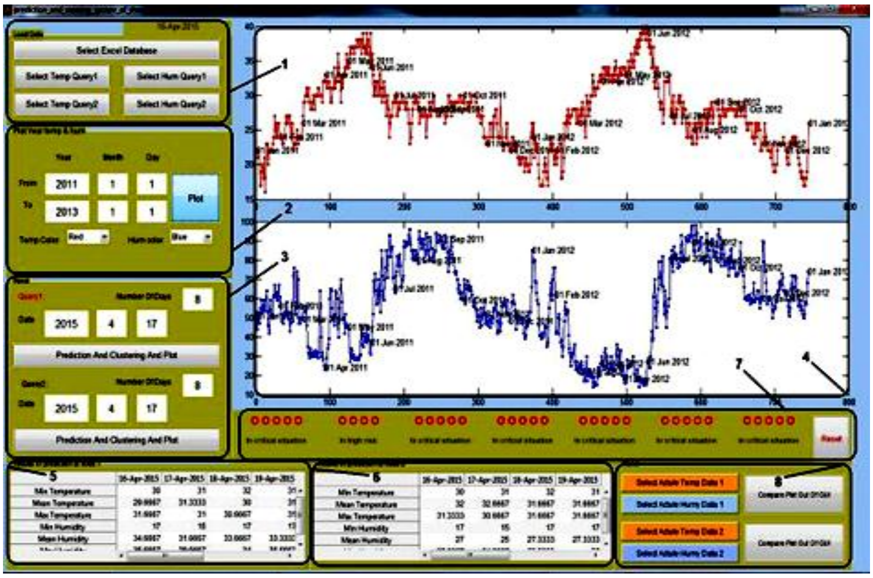

Figure 28: An overview of graphical user interface (GUI) for temperature and humidity prediction section

Section 1: In this section, the files containing the database information and queries 1 and 2 that each contains one file for temperature and one file for humidity (five Excel files in total) will be uploaded as input.

Section 2: this section provides the ability to display and select any date or range of data in the database (for the times when we want to take a closer look at historical profile of the bridges and climatic conditions of its location in a specific period).

Section 3: this section provides user to enter his desired date for prediction based on data of first or second node and also enables user to choose the number of days after that date for prediction.

Section 4: this section displays the prediction charts and the historical profile for user's desired time period.

Section 5: this section displays average, maximum and minimum values for humidity and temperature in Node 1.

Section 6: this section displays average, maximum and minimum values for humidity and temperature in Node 2.

Section 7: this section displays the alarm level and provides the possibility of resetting it.

Section 8: this section provides the possibility of making a visual comparison between the predicted values of temperature and humidity in nodes 1 and 2 and actual values measured by the proposed SHM systems.

It should be mentioned that this simulation system has the ability of issuing an alarm and warning to maintenance personnel of the bridge. The mechanism of this warning system includes deriving 5 levels of alert (which will be thoroughly discussed in the upcoming sections) though conducting fuzzy analysis on humidity and temperature values and through a fuzzy instruction set and designing a fuzzy inference system (FIS). These alert levels will be displayed in GUI the predicted values for temperature and humidity for each given day. In addition, the ability of resetting these levels for next predictions is also embedded in the GUI.

The specifications of designed Mamdani FIS for alarm system are as:

A-First input: Temperature
3 membership function: Low, medium, high
input range between 0 and 50 degrees.

B-second input: Humidity
3 membership function: Low, medium, high
input range between 0% to 100% (% RH)

C- Output: Alarm Level
5 membership function: One, two, three, four, five
output range between 0 and 5

There are 9 rules for the above FIS system which are as follows:
1. If (temperature is low) and (humidity is low) then (alarm-level is one)
2. If (temperature is low) and (humidity is medium) then (alarm-level is two)
3. If (temperature is low) and (humidity is high) then (alarm-level is four)
4. If (temperature is medium) and (humidity is low) then (alarm-level is one)
5. If (temperature is medium) and (humidity is medium) then (alarm-level is three)
6. If (temperature is medium) and (humidity is high) then (alarm-level is four)
7. If (temperature is high) and (humidity is low) then (alarm-level is two)
8. If (temperature is high) and (humidity is medium) then (alarm-level is four)
9. If (temperature is high) and (humidity is high) then (alarm-level is five)
Weighted average method is used for defuzzification.

The System with the above specifications determines an alarm level for predicted values based on the details of the inputs and output and through using fuzzy inference techniques. They include:

1) ideal
2) Suspicious
3) at risky conditions
4) in high risk conditions
5) in critical situation

With these alarms, bridge maintenance personnel can perform proactive maintenance operations with greater efficiency and before temperature and humidity values reach critical conditions in order to prevent the growth and spread of the damage and to fix it with minimum cost when damage is still in its initial stages. At the end of the third section of article, we will mention some examples of the application of the above system in bridge maintenance. On the other hand, the possibility of comparing and validating the above predicted values with actual data is provided in our SHM system. The Figure 29,30,31 figures show one example for each of the nodes.

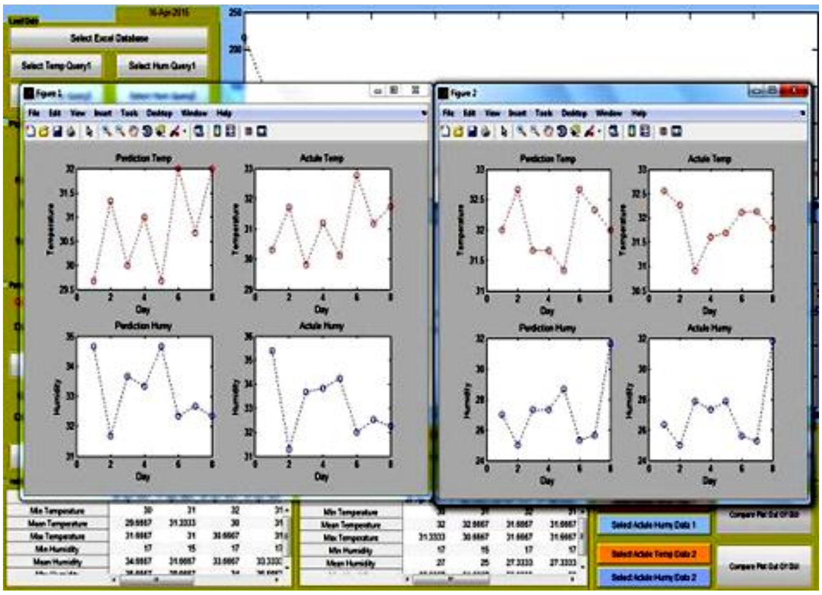

Figure 29: Comparison of predicted temperature and humidity values with the actual values recorded by SHM system

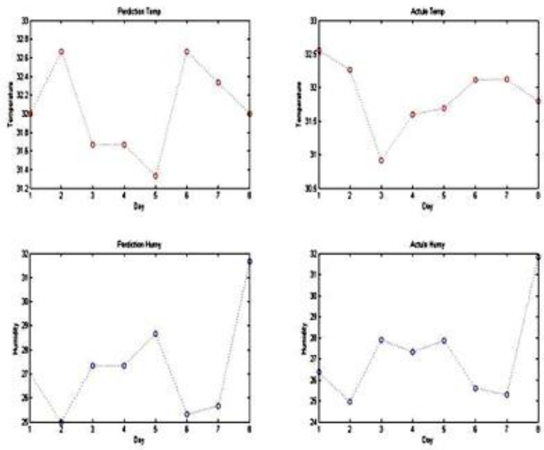

Figure 30: Comparison of predicted temperature and humidity values in node 1 with the actual logged values

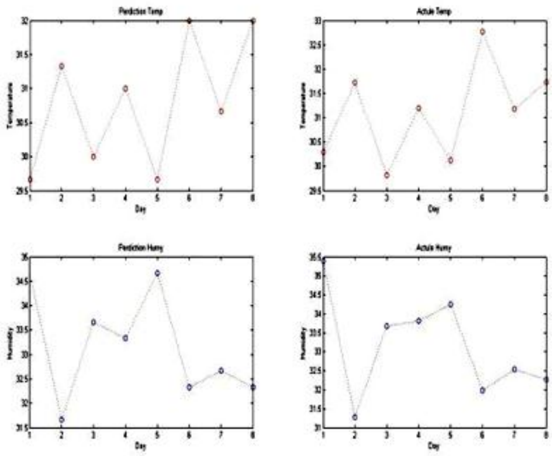

Figure 31: Comparison of predicted temperature and humidity values in node 2 with the actual logged values

Calculations showed that mean squared error (MSE) of the prediction was about 0.143 for temperature and 3.601 for humidity.(Figure 32).

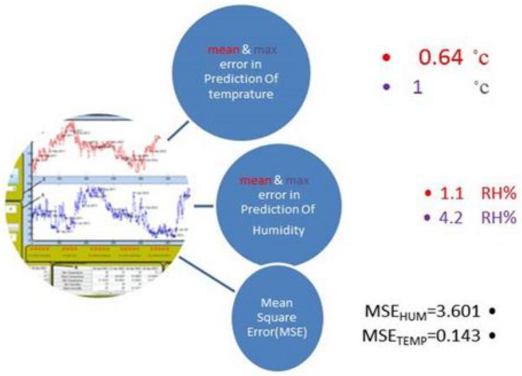

Figure 32: Maximum error, mean error and MSE values for the temperature and humidity predicted by the proposed system.

Conclusion

In this study, a system with multiple functions for monitoring the structural health of a medium sized assumed bridge (length of 50 meters, height of 10 meters, and with 6 piers), 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.

To monitor the temperature and humidity, sensor nodes include two end nodes which both have LM35 sensor for temperature and HIH4000 sensor for humidity and a coordinator node in which data is acquired, processed and stored by the LABVIEW software. The mean errors in the calculation of temperature and humidity values were (1 degree) and (2.5 degrees) respectively; the maximum error in the calculation of temperature and humidity values were (1.7 degrees) and (4.2 degrees) respectively; mean squared error in the calculation of temperature and humidity values were(1.651 degrees) and (2.192 degrees) respectively. The data of a wired SHT11 digital sensor was used as the reference and standard for measuring the errors.

In this study, proposed SHM monitoring system has been equipped by a novel method of using data mining techniques (KNN algorithm) on temperature and humidity data of past few years related to the location of the bridge to predict the temperature and humidity values in the nodes, and this ability has upgraded it from a simple monitoring system to a proactive system of maintenance. On the other hand, using a fuzzy inference system provided the possibly of issuing alerts and messages based on fuzzy analysis on the predicted values of temperature and humidity to move toward total productive maintenance (TPM) and proactive maintenance. The mean errors in the prediction of temperature and humidity values were (0.64 degree) and (1.1 degrees) respectively; the maximum error in the prediction of temperature and humidity values were (1 degree) and (4.2 degrees) respectively; mean squared error in the prediction of temperature and humidity values were (0.143 degree) and (3.601 degrees) respectively.

The data of monitoring system was used as the reference and standard for measuring the errors of the prediction section of MA 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 systems -which at this stage is still a combination of hardware and simulation- can be used for the long-term and real-time monitoring of medium-sized to large-sized bridges MATLAB program.

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 systems -which at this stage is still a combination of hardware and simulation- can be used for the long-term and real-time monitoring of medium-sized to large-sized bridges.

5. SUGGESTIONS FOR FUTURE WORKS

Measures that can be taken to improve this study are as follows:

- Providing all nodes with the ability of sensing all four parameters of temperature, humidity, displacement and stress-strain and integration of related programs and applications in the form of user friendly software for the bridge supervisor.
- Integration of proposed SHM systems with traffic control centers and smart energy networks.
- Equipping the proposed system with new ideas in the discussion of structural health monitoring, including the use of strain gauges, FBG, optic fibers, RFID.
- Designing the nodes with the ability of energy harvesting for this SHM system.
- Expanding the platform designed for this SHM for other structures and applications, especially for the structures, installations, and pipelines in oil and gas extraction and transportation industry and other related sectors.

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