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A case study for application of fuzzy inference and data mining in structural health monitoring

S. Shoorabi Sani*

Faculty of Electrical and Computer Engineering, Hakim Sabzevari University, Iran.

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**Corresponding author: s1sani91@gmail.com (S. Shoorabi).*

Abstract

In this work, a system is designed for monitoring the structural health of bridge deck and predicting various possible damages to this section based on measuring the temperature and humidity using wireless sensor networks, and then it is implemented and investigated. A scaled model of a conventional medium-sized bridge (of 50 m length and 10 m height, and with 2 piers) is examined for the purpose of this work. 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 the temperature and humidity values is received using a LABVIEW-based software to be analyzed and stored in a database. The proposed structural health monitoring (SHM) system is equipped with a novel method 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 the analysis of bridge conditions by the 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 the total proactive maintenance (TPM). Very low costs, increased efficiency of the bridge service, and reduced maintenance costs make the SHM system a practical and applicable one. The data and results related to all mentioned subjects are thoroughly discussed, and the accuracy and reliability of the SHM systems are evaluated. The results obtained show that this system is qualified to be used as a SHM system in a sample *hypothetical* bridge.

Keywords: *Structural Health Monitoring, Wireless Sensor Networks, Proactive Maintenance of Bridges, Data Mining and Fuzzy Inference Techniques.*

1. Introduction

Maintaining the safety and a 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, and decrease in the load capacity of the bridge, all of which should be carefully evaluated. Common measurements such as periodic visual inspections and controlled loading test are typical in this respect, and their disadvantages have been thoroughly investigated. A new technology called structural health monitoring (SHM) that uses 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 the damages to the bridge structure through analyzing the dynamic characteristics of the bridge such as shifts in the pier frequencies and changes in the vibration modes and assessing the structural damping index or modal assurance criterion. The characteristics of low-frequency pier vibrations are not sensitive to small damages and changes in the structure, so the monitoring systems have to cover higher frequencies to detect such changes [9], and this necessarily requires a significant number of highly sensitive transducers and also a data acquisition system with a high rate of sampling [10]. 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 the natural frequencies caused by structural damage can be easily overlooked under the influence of environmental effects, especially changes in temperature and humidity [11-19]. The presence of these difficulties and limitations [20-26] is the main motivation for the investigation of other SHM methods for bridges. In this work, a SHM system that utilizes the wireless sensor networks (WSNs) and is based upon monitoring humidity and thermal environmental responses was designed, and it was then analyzed with the help of a hypothetical bridge. A researcher has claimed that this method has the ability to by-pass 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 [12,13,14]. 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 in 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]. The slow and wide-range changes facilitate the use of thermal response methods such as measuring the temperature in different parts of the bridge that can be easily monitored. This monitoring can be easily performed through conventional and inexpensive transducers and data acquisition systems that have low sampling rates and can simultaneously monitor the environmental heat loads and the responses of the bridge. The condition of a 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 a large amount of valuable data than can be used to perform calculations in a comprehensive manner and on a daily basis. In addition, the thermal responses are semi-static, so the 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 that of the underside of the deck, and this causes the bridge flexure to be drawn upward. For a typical curved bridge, this phenomenon has a little effect on the reaction of the pier section or the 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 causes thermally induced momentary stresses and strains along the bridge flexure. These thermally induced responses are a function of EL. Therefore, the cracks and damages in the curved sections of the bridge can substantially alter the effective EL of the bridge [15, 16]. In view of the above discussion, a SHM based on environmental thermal responses seems to be suitable for long bridges with several curves. The main focus of this research work is on the pre-stressed concrete bridges with medium to high curve lengths. This study also examines the evaluation and monitoring of the effect of humidity on different parts of the bridge and also the corrosion and damage caused by humidity or those damages for which humidity acts as an accelerating factor. The results obtained showed that a well-designed and well-implemented SHM system based on environmental thermal responses and humidity has the ability of detecting the structural damages and identifying their location and severity [17,18].

It seems necessary to state clearly why we use KNN instead of the other similarity measures at the data mining stage of this research work. Nearest neighbor search (NNS), also known as proximity search, similarity search or closest point search, is an optimization problem for finding the closest (or most similar) points. Closeness is typically expressed in terms of a dissimilarity function: the less similar the objects, the larger the function values. Formally, the nearest-neighbor (NN) search problem is defined as follows: given a set S of points in a space M and a query point q ∈ M, find the closest point in S to q. Donald Knuth in Vol. 3 of The Art of Computer Programming (1973) called it the post-office problem, referring to an application of assigning to a residence the nearest post-office. A direct generalization of this problem is a k-NN search, where we need to find the k closest points.

Most commonly, M is a metric space, and dissimilarity is expressed as a distance metric, which is symmetric and satisfies the triangle inequality. Even more common, M is taken to be the d-dimensional vector-space, where dissimilarity is measured using the Euclidean distance, Manhattan distance or other distance metric. However, the dissimilarity function can be arbitrary. One example is the asymmetric Bregman divergences, for which the triangle inequality does not hold.

The simplest solution to the NNS problem is to compute the distance from the query point to every other point in the database, keeping track of the "best so far". This algorithm, sometimes referred to as the naive approach, has a running time of O(dN),where N is
the cardinality of S and d is the dimensionality of M. There are no search data structures to maintain, so a linear search has no space complexity beyond the storage of the database. A naive search can, on average, outperform space partitioning approaches on higher dimensional spaces.
Since the 1970s, branch and bound methodology has been applied to the problem. In the case of the Euclidean space, this approach is known as the spatial index or spatial access method. Several space-partitioning methods have been developed for solving the NNS problem. Perhaps the simplest is the k-d tree, which iteratively bisects the search space into two regions containing half of the points of the parent region. Queries are performed via traversal of the tree from the root to a leaf by evaluating the query point at each split. Depending on the distance specified in the query, the neighboring branches that might contain hits may also need to be evaluated. For a constant dimension query time, an average complexity is O(log N). In the case of randomly distributed points, the worst case complexity is $o(kN^{(1-\frac{1}{k})})$. Alternatively, the R-tree data structure was designed to support the nearest neighbor search in dynamic context, as it has efficient algorithms for insertions and deletions such as the R* tree. R-trees can yield the nearest neighbors not only for the Euclidean distance but can also be used with other distances. Particular examples include VP-tree and BK-tree.
Using a set of points taken from a 3D space and putting into a BSP tree, and given a query point taken from the same space, a possible solution to the problem of finding the nearest point-cloud point to the query point is given in the following description of an algorithm. (Strictly speaking, no such point may exist because it may not be unique. However, in practice, usually we only care about finding any one of the subsets of all point-cloud points that exist at the shortest distance to a given query point.) The idea is, for each branching of the tree, to guess that the closest point in the cloud resides in the half-space containing the query point. This may not be the case but it is a good heuristic. After having recursively gone through all the troubles of solving the problem for the guessed half-space, now compare the distance returned by this result with the shortest distance from the query point to the partitioning plane. This latter distance is that between the query point and the closest possible point that could exist in the half-space not searched. If this distance is greater than that returned in the earlier result, then clearly, there is no need to search for the other half-space. If there is such a need, then you must go through the trouble of solving the problem for the other half space and then compare its result with the former one, and then return the proper result. The performance of this algorithm is nearer to the logarithmic time than the linear time when the query point is near the cloud since as the distance between the query point and the closest point-cloud point nears zero, the algorithm needs only perform a look-up using the query point as a key to get the correct result.
On the other hand, due to the repeatability of weather periods in terms of the effective parameters in different weather conditions like temperature, humidity, and wind speed, their repeat pattern is so complicated and is beyond the scope of this research work. The nearest neighbor algorithm can search similar weather conditions which are dominant in the recent days in the location of bridge in different parts of its structure that they are measured and logged by the SHM system in this article, which will be saved -at the preset time interval - in a data bank which is involved in weather parameters' profile related to the recent years of the location of the bridge.
This system has the ability to provide alarms and warnings -for Total Proactive Maintenance (TPM) principles before damages and crisis situations occur-. All the above-mentioned methods will be introduced, investigated, and evaluated thoroughly in the second and third parts of this article. Also it should be noted that in this article we will assess measurement of pair parameters of temperature and humidity due to the easier measurements and cheaper equipment for logging data regarding to temperature and humidity parameters. .Their important effects on health of bridges' structure are studied in different recent researches [10-14].
The second section of this article introduces the details of the proposed SHM system and its implementation, the hardware and configuration of the sensor network, and designed monitoring program. Then discusses the manner of improving the proposed method to a proactive system with the ability to predict the temperature and humidity using the especial data mining techniques. The third section assesses and evaluates the results of the proposed SHM, average and maximum error,

and mean squared error, whether in the measurement stage or in the process of predicting the temperature and humidity. This section also assesses the details of a warning system based on the fuzzy inference. The final part of the third section presents some examples of the practical applications of the proposed monitoring system in the maintenance procedures of conventional bridges. The fourth section summarizes the discussed issues and the advantages 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 work, a SHM system with the following characteristics was designed, implemented, and simulated for a hypothetical bridge. An overview of the proposed SHM system and its components and functions is shown in figure 1.

Figure 1. An overview of proposed SHM system and its components and function.

As shown in figure 2, the parameters temperature and humidity are monitored at two points of the bridge deck. This data will be used for the data mining process and prediction of the critical values for the following days, and a warning system based on the fuzzy inference techniques will assess the status of the mentioned points, and will announce timely pre-emptive alerts to the repair and maintenance team.

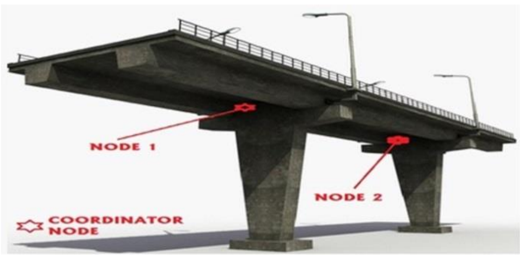

Figure 2. SHM systems of presumed bridge and layout of its components [7].

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

The inexpensive and analog sensors LM35 and HIH4000 were used for sensing and measuring the temperature and humidity, respectively, for the design of the nodes of a wireless sensor network. To assess the reliability and accuracy of the system, the 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. The sensor nodes were designed using the Protel (Altium Designer) software. Figure 3 shows the layout of PCB used.. This design includes a board for the LM35 and HIH4000 analog sensors and a separate board for the SHT11 sensor, which is considered as a reference for the measurement. Figure 4 shows the final view of the above-mentioned designs.

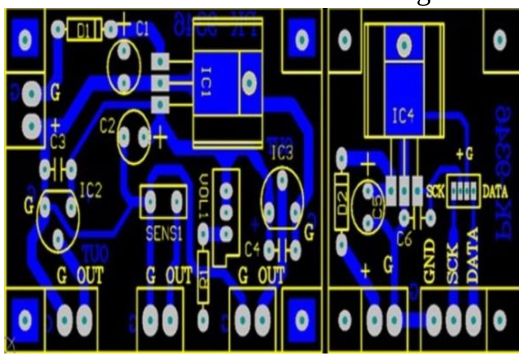

Figure 3. layout of PCB of board and bias circuits of temperature and humidity sensors.

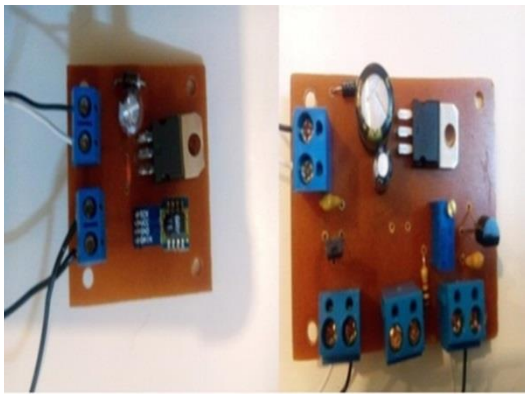

Figure 4. Final image of sensor nodes (analog nodes including LM35 and HIH4000 sensors on the right, and SHT node on the left).

In the next step, the ProBee-ZE10 ZigBee module was used as the wireless module. The default development board of this device was used to ensure an easier application and also for an easier installation of the connectors. The image of this module and its development board can be seen in the figures 5 and 6, respectively.

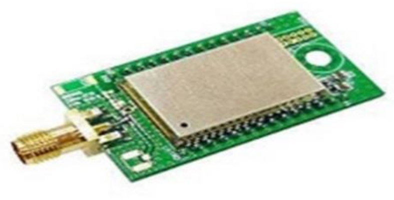

Figure 5. Image of ZE10 module [2].

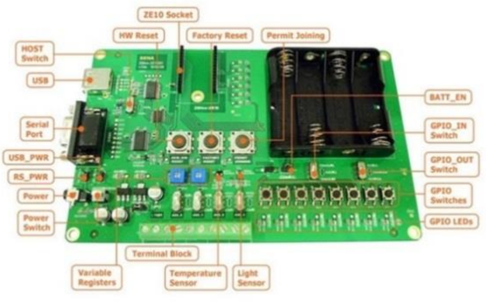

Figure 6. Image of ZE10 development board [2].

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

In the coordinator node connected to a computer through a USB port, the values related to the analog channels 3 and 4 (the temperature and humidity) in each node can be read and received through the especial commands [1].

After sending the above data string in the 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 the coordinator node (with about 2 to 3 seconds delay), and then will enter in the software through a serial port. The Labview software will perform the processes of retrieving and separating data strings and converting hexadecimal data to decimal, then applies calibration coefficients to obtain correct values for temperature and humidity, and subsequently, 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 node 1 and “hum2” and “temp2” for node 2. Figure 7 shows further details of the front panel of this software.

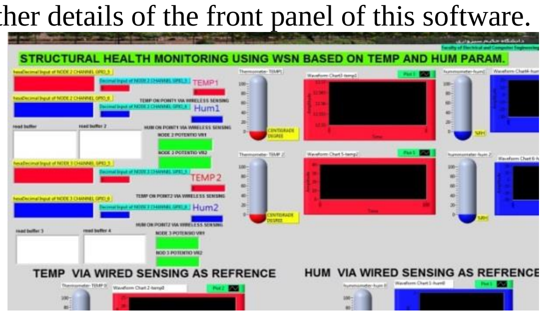

Figure 7. Front panel of software.

In this panel, all the received values and data strings and all the operations performed on them at each step can be easily reviewed by the user through String indicators. It also plots a graph for temperature and humidity at each node, and a graphical barometer separately shows the accuracy of the system performance. The values that are stored in the Excel files are also displayed in this application. Actually, in the front panel of the software, we can see the values (strings or digits) for all steps of the sending and receiving data including the first start string that is sent via the coordinator to the two end notes for initializing the A/D channel and making the A/D conversion.

Also we can see the hexadecimal input of the global propose input and output of the wireless modules, decimal values of the raw data for temperature and humidity, and trend or waveform of the temperature and humidity parameters. Also we can see the temperature and humidity values and graphs from SHT11 as the reference data.

The main parts of the temperature and humidity monitoring application, which is based on the LABVIEW coding language (in node1, for example) and the SHT11 sensor data acquisition application are shown in figures 8a-d. In figure 8a, in rectangle 1, the serial port of the computer is configured and the parity, bit-rate, and other necessary parameters for the wireless channel are set. In rectangle 2, the received string is devised via an “un-concatenate” block, and in rectangle 3, the strings are converted to the decimal digits and form the raw temp data. Finally, in rectangle 4, the raw data is scaled and/or offset to provide the final temperature value. Similar explanations exist for the humidity at the 4 rectangles in figure 8b. In figure 8c, the configuration of the port and serial and wireless communication channel is done in rectangle 1, and converting the received string to the final temperature value is done in rectangle 2. Similar explanations exist for the humidity at 2 rectangles in the figure 8d.

2.4. Implementation of temperature and humidity monitoring system

In the next step, 3 selected wireless modules were configured. 2 modules were defined as the end device and one module was defined as the coordinator. Configuration of the end devices and coordinator was performed through the USB terminal of a laptop and by the use of the Hyper Terminal software. These settings are also available through the pro-Bee manager software. There are 4 analogs to the 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 the initial and required tests of the program, and channels 2 and 3 were dedicated to connecting the output of the temperature and humidity sensor in each node, respectively. After performing the initial configuration of all nodes and connecting the sensors and feeds of all the three nodes, the sensor network will have the overall configuration as shown in figure 9. The final configuration of the two end nodes (node 2 & node 3) and one coordinator node (node 1) are shown in figures 10-12, respectively. On the other side, figure 13 shows the reference digital sensor and its Data Acquisition (DAQ) board.

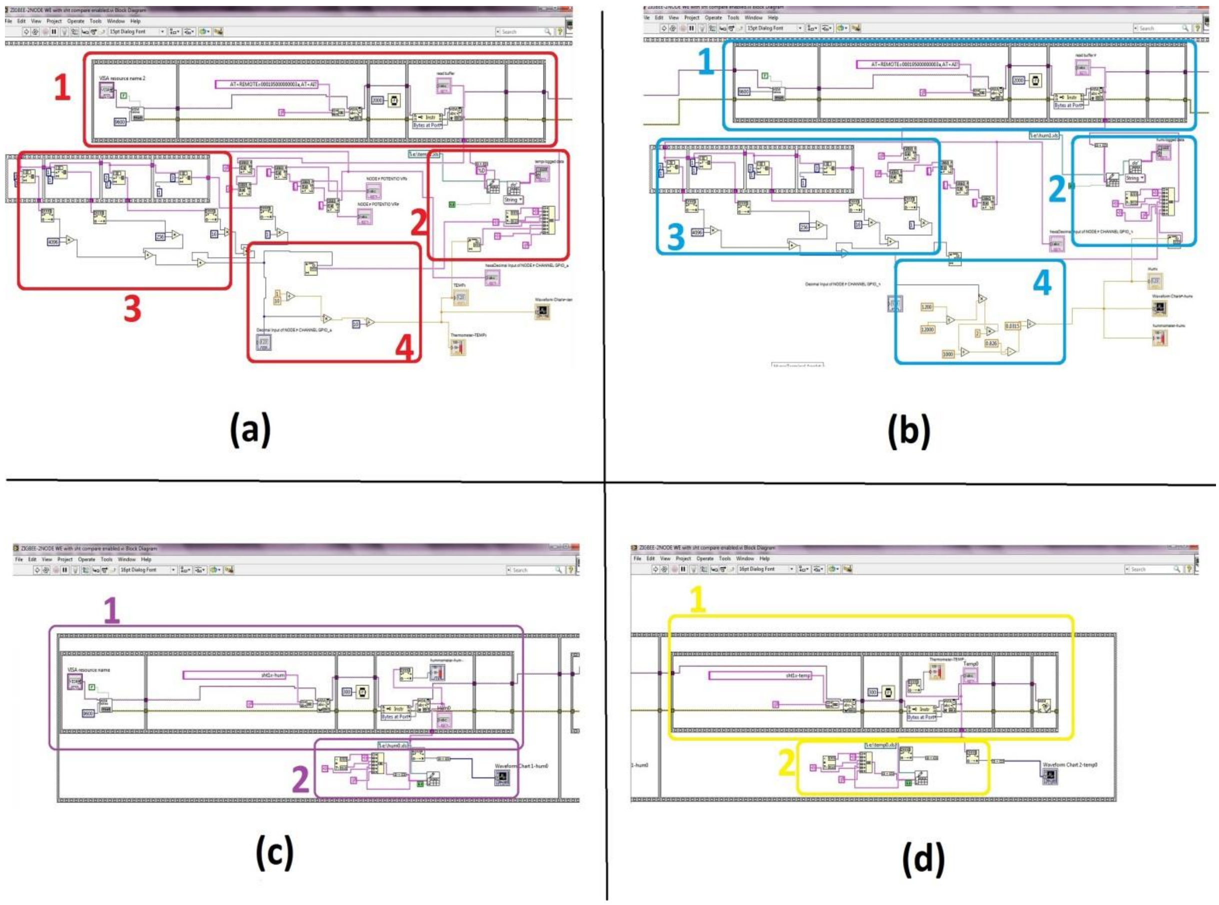

Figure 8. a)Wireless temperature measurement program for node 1, b) Wireless humidity measurement program for node 1, c) SHT11 sensor data acquisition program for temperature, d) SHT11 sensor data acquisition program for humidity.

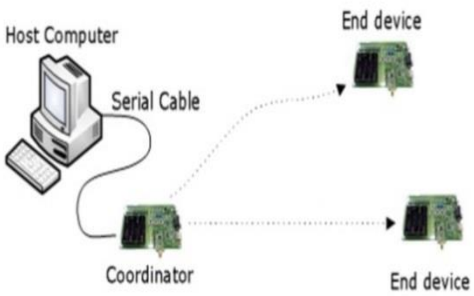

Figure 9. Overall configuration of wireless sensor network used in SHM system.

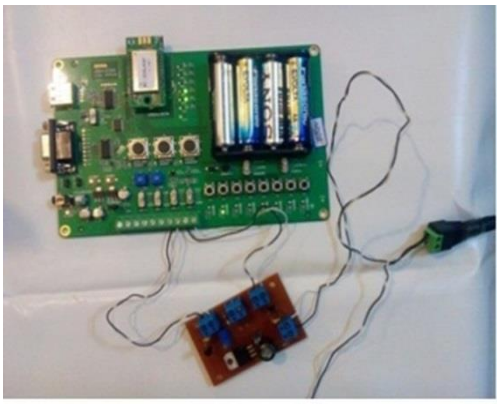

Figure 10. Node 2 (end node).

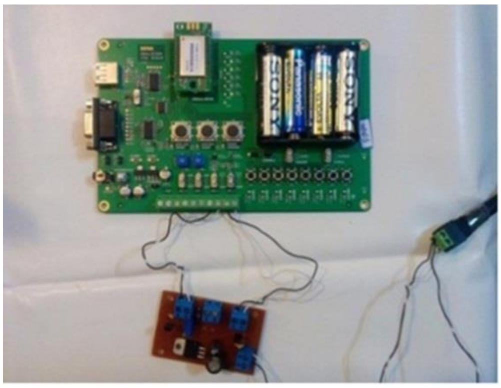

Figure 11. Node 3 (end node).

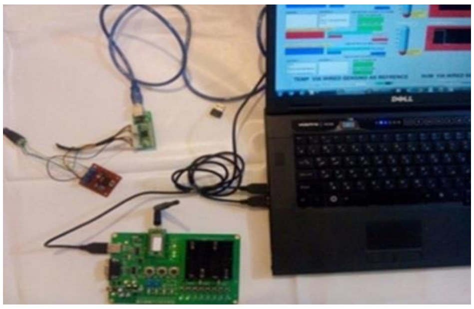

Figure 12. Mother node (COORDINATOR) + PC.

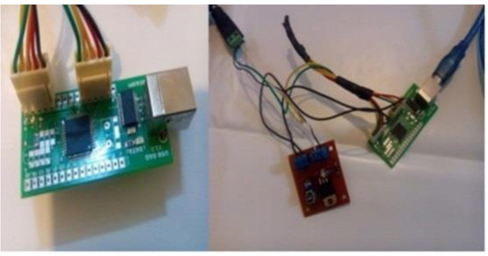

Figure 13. SHT11 digital sensor board + USB DAQ.

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

After formation of the 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 3 years in the area where the bridge is located). The details of this method are as follow.

The basis of this method is to use the temperature and humidity data for the past 3 years (collected in a database and sorted based on different months) and the temperature and humidity data the last 3 days recorded on the "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 (K-NN) to predict the temperature and humidity for the desired date. If the values for this predicted data exceed the limits (alert level) determined by the fuzzy technique, the system will notify the maintenance personnel to perform proactive or predictive maintenance and repair procedures on the bridge. A graphical interface was designed for the user's convenience, the details of which will be discussed in the third section of the 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.

2.6. Dataset

The most important part while implementing any data related project is the collection of the proper data for the analysis using any technique (e.g. data mining). To test the algorithms in this research work, a huge amount temperature and humidity data was required for the large number of days or years. Hence, the dataset for a duration of three years was collected from the similar proposed SHM system [21]. The data regarding to the various parameters are obtained in excel format from the proposed SHM system in figure 14. The required parameters- i.e. temperature and humidity -can be extracted from these datasets and then can be exported in MATLAB files where they are available for more analysis. Figure 14 shows the schematic representation of the above-mentioned CSV file in the excel arrangement that includes temperature, dew point, humidity, sea level press, etc. In this research work we focused on the two parameters "temperature" and "humidity" because the equipment required for measuring them had a lower price with respect to those of the other parameters.

On the other hand, the average amount of humidity and temperature in the last 3 days was recorded by monitoring the system in the "hum1" and "temp1" files for node 1 and "hum2" and "temp2" for node 2; this dataset is called "query". The overall layout of the above technique used to predict the temperature and humidity is described in the following section.

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

Figure 14. Database (sorted in Excel file).

2.7. Aggregation, converting raw data

The algorithm in this research work takes the monthly temperature and humidity data as the input. The data is available in the excel format, and for the analysis of the temperature and humidity variation throughout the year, the monthly data need to be aggregated in one file. After aggregations, three matrices were formed for the years 2012, 2013, and 2014. Each column of a matrix represents the date (day of month/year) whereas each row consists the values of the temperature and humidity on a particular day(date).

For the purpose of temperature and humidity prediction, only the data for these parameters from the raw dataset is required, and hence, they must be extracted. Thus the temperature and humidity data for each month was extracted and stored in Matrix format named by the particular month. Only the values for temperature or humidity in a particular month of a year will have a maximum resemblance to its values for that particular month for any other year, and hence twelve matrices are created for these data for each month of the year as Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sept, Oct, Nov, and Dec, These consist of the temperature and humidity data for that respective month for the complete duration of the three years 2012, 2013, and 2014. The data for more years can be added to this. These dataset matrices are then used for the prediction of temperature and humidity.

2.8. Implementing K-nearest neighbor for temperature and humidity prediction input

dataMatrix // Candidate trace data matrix for a particular month for duration of 4 years
(2012, 2013, 2014)
queryMatrix // Reference trace data matrix consists of data for previous 3 days to the day of prediction
K // Number of neighbors, K=4 in this research work.
Output:
mtP[4] // Predicted Temperature values for 4 days
mhP[4] // Predicted Humidity values for 4 days
dataMatrix // Candidate trace data matrix for a particular month for duration of 4 years
(2012, 2013, 2014)
queryMatrix // Reference trace data matrix consists of data for previous 3 days to the day of prediction
K // Number of neighbors, K=4 in this research work.
Output:
mtP[4] // Predicted Temperature values for 4 days
mhP[4] // Predicted Humidity values for 4 days
KNN Algorithm: // Algorithm to predict temperature and humidity
Step 1: Initialize variables
numDataVectors = size of dataMatrix
numQueryVectors = size of queryMatrix
Step 2: Initialize For i = 1 to numQueryVectors
Calculate Euclidian Distance.
Sort Euclidian Distances and neighborIds in ascending order.
Calculate
NeighborDistance(i) = sqrt(sortval(i to k))
End for loop
Step 3: Initialize i = 1 to 3
Initialize i = 1 to 4
tP (i, j) = dataMatrix(2)
hP (i, j) = dataMatrix(3)
end loop
end loop
Step 4: Calculate predicted temperature and humidity
mtP = tP/3
mhP = hP/3
return predicted temperature and humidity.
Step 5: Exit

2.9. Working of KNN Algorithm

Figure 15 shows the working of KNN algorithm for the temperature and humidity prediction. Figure 15(a) shows two matrices, dataMatrix and queryMatrix. DataMatrix consists of the temperature and humidity data for three years for the months whose prediction is to be made. For example, if the prediction is to be made for 28-2-2015, then dataMatrix consists of the temperature and humidity data for the month February for the years 2013, 2014, and 2015; The size of the matrix so formed is 113 x 2. QueryMatrix consists of the temperature and humidity data for 25-2-2015, 26-2-2015, and 27-2-2015. The KNN algorithm calculates the four nearest neighbor (NN) for the temperature and humidity data for each day of queryMatrix. The index for all of these neighbors for each day is shown in neighbors matrix in figure 15(b), and the Euclidian distance is shown in Dist matrix in figure 15(c); the rows in Dist matrix indicates the ith day in queryMatrix, and the ith column indicates the ith NN for temperature and humidity for the ith day.

Figures 15(d) and 15(e) show the temperature and humidity values from dataMatrix for the index obtained in neighbors matrix. The average values of the ith column in tP and hP matrix give the predicted values for temperature and humidity for the ith day. Figure 15(f) shows the predicted values for temperature and humidity for four days, i.e. 28-2-2015 to 2-3-2015. The mean square error was calculated for the above prediction, and it was found to be 1.65 for the temperature prediction and 2.192 for the humidity prediction. A discussion is presented in more details in section 3.2. For the other similar data mining techniques refer to [23].

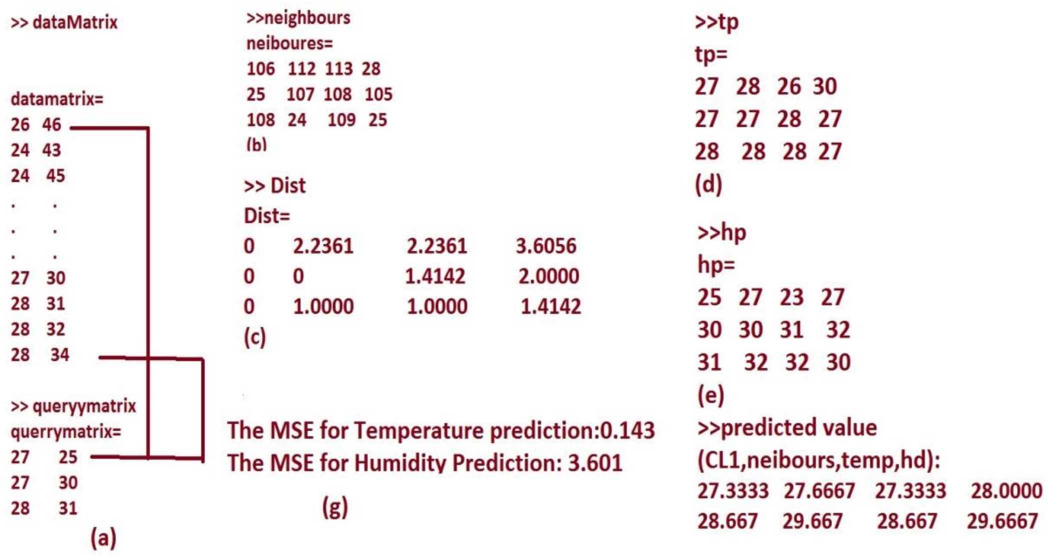

Figure 15. Overall layout of NN algorithm.

2.10. Clustering

In this research work, the datasets were divided into a number of clusters based on the type of analysis required. Regarding to the 'Clustering' method which is used here, figure 22 (which will be discussed later in section 3 in more details) shows an example of the procedure which is used to create the clusters for the month April. The clustering output forms a data matrix of size 90 X 3, which consists of the date temperature and humidity values for April for the years 2012, 2013, and 2014. The cluster formed is shown in figure 23. Twelve such clusters for each month from January to December are already created in the system based on the three years dataset. In the same way, 38 clusters for all months from January 2012 to February 2015 were created, and 6 clusters were already stored in the database for temperature and humidity 2 for the years 2012, 2013, and 2014.

3. Evaluation of proposed SHM

3.1. Evaluation of real-time monitoring of temperature and humidity

The SHM-related parameters can be assessed based on the humidity and temperature values for the proposed monitoring system. As mentioned earlier in the introduction section, temperature and humidity can cause damage to the bridge structure including cracking caused by temperature gradient (itself caused by the different degrees of sunlight on the different parts of the bridge), corrosion caused by humidity and climatic factors (corrosive sea salts), and the corrosion and damage that have different origins but in which humidity and temperature act as the accelerating factors. In this section, the short-term measured data and graphs are presented for the proposed monitoring system for two points. An example of the temperature values logged in the Excel files (TEMP1, TEMP2) and an example of humidity values logged in the Excel files (HUM1, HUM2) are shown in tables 1 and 2 , respectively.

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

TEMP REFFRENCE SHT11	Temperature Celsius degree	TIME	DATE
27.7	29	5.19pm	04/14/2015
27.7	29	5.20pm	04/14/2015
27.5	29	5.21pm	04/14/2015
27.5	29	5.22pm	04/14/2015
27.5	29	5.23pm	04/14/2015
27.5	29	5.24pm	04/14/2015
27.5	29	5.25pm	04/14/2015

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

HUM REFFRENCE SHT11	HUMIDITY RH%	TIME	DATE
35	38	5.18pm	04/14/2015
36	38	5.19pm	04/14/2015
36.3	37	5.20pm	04/14/2015
36.3	36	5.21pm	04/14/2015
36.3	39	5.22pm	04/14/2015
36.3	37	5.23pm	04/14/2015
36.3	38	5.24pm	04/14/2015

It is worthy to note that these two tables are just as examples for proving the accuracy and reliability of the proposed system results with respect to the reference data which is obtained from the sht11(digital sensor) reference input. Assessment of the temperature and humidity values and their comparison of with the critical threshold values at different points provide the possibility of detecting the present structural issues (or those that are going to happen). To assess the accuracy and reliability of the proposed system, it was deployed for 3361 minutes (approximately two and a half days) to store the temperature and humidity data, and then the results obtained were compared with those for the SHT 11 sensor, for which the digital temperature and humidity data was collected through a data acquisition card. Figure 16 shows the temperature data that was stored by wireless monitoring, and figure 17 shows the temperature data that was stored by the wired SHT11 sensor in the same period.

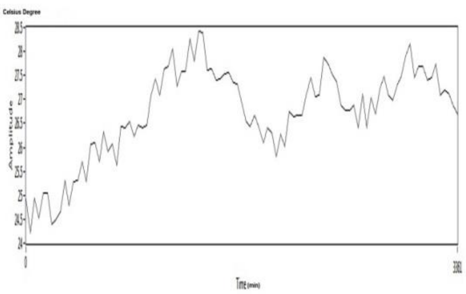

Figure 16. Temperature data stored by wireless sensor network monitoring system and LM35 analog sensor.

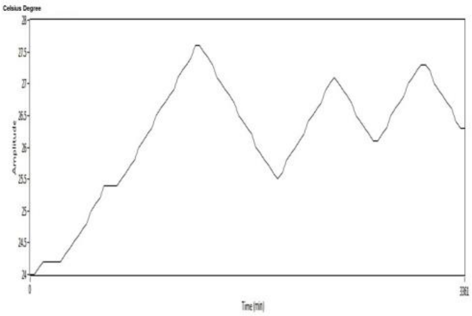

Figure 17. Temperature data stored by wired SHT11 digital sensor.

The humidity data logged by wireless sensor network monitoring system and HIH400 analog sensor is shown in figure 18 and the humidity data logged by the wired SHT11 digital sensor is shown in figure 19.

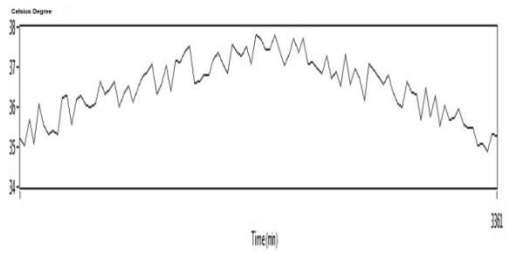

Figure 18. Humidity data logged by wireless sensor network monitoring system and HIH400 analog sensor.

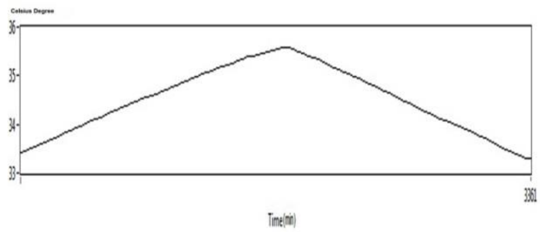

Figure 19. Humidity data logged by wired SHT11 digital sensor.

Relative error of proposed SHM system in the calculation of temperature and humidity is shown in figure 20.

According to the assessments and the results of similar studies, discussed in the introduction section, the thermal response of the bridge structure (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 the structure to these elements. According to the studies mentioned in the the introduction section [19,20,21], the total longitudinal tensile strain (εT) at the height of (y) from under the arch of the bridge in one of its sections is:

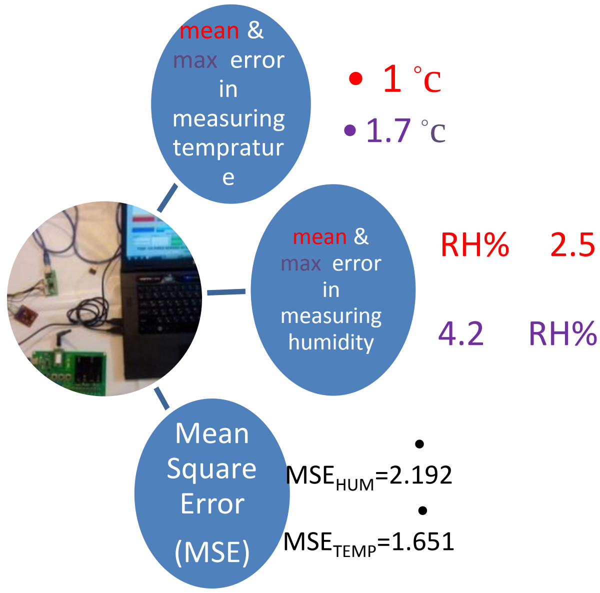

Figure 20. Maximum error, mean error, and MSE values for temperature and humidity parameters monitored by proposed system.

$$\varepsilon_T(Y) = \varepsilon_b - \psi_b y \qquad (1)$$

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:

$$\varepsilon_m = \varepsilon_T - \varepsilon_f \qquad (2)$$

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

$$\sigma(y) = E\,\varepsilon_m = E(\varepsilon_T - \varepsilon_f) \qquad (3)$$

where, E is the modulus of elasticity of the material (concrete in this case). On the other hand, according to the results of the model proposed and proved in [19,20,21], we have:

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

In the above equation, β is a dimensionless function of X. The β values 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 for the β function is known, the thermal response of a damaged bridge can be estimated and calculated by equation (3). However, in this study, our aim was to determine β (refer to Figure 21 [20]).
Determination of β through matching and assessing the predicted values [19,20,21] and the thermal response of the damaged bridge (obtained from the proposed monitoring system) will enable us to identify and map the distribution and severity of the damages (fractures and wave-form cracks) in the bridge.

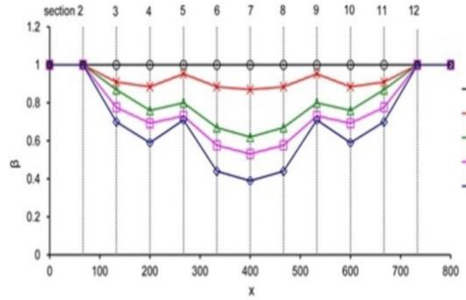

Figure 21. β function as an indicator of severity and location of damage in model structure [20].

The mentioned idea is the basis of the proposed method in order to detect the structural damages using the thermal response of the structures [19, 20, 21]. As it can be seen, the β function shows that the extent of damage to the wave-form fractures in the model bridge mentioned in [19, 20, 21] is proportional to the levels of damage of CS1, CS2, CS3, CS4, and CS5, which increase in that order. On the other hand, the structural thermal response and profile will be determined through the 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 [19,20]. Overall, the $\varepsilon_T, \varepsilon_f$ parameters in (3) will be determined by the thermal response monitored by the system, and then $\sigma(y)$ (mechanical stress) will be calculated at each y, and in the end, once all the parameters are determined, β will be obtained. For more details for the SHM system details and the procedure for the damage identification, refer to our previously published work [22].For other similar data mining techniques refer to [23].

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

A graphical user interface (GUI) was designed to facilitate the data entry and display the outputs for the application section that predicts the temperature and humidity to prevent the spread of the damage and to guarantee the predictive and proactive maintenance and repair.
This GUI was designed by the C# software, and about 700 lines of code were added to link the tags to the main program of the KNN algorithm. An overview of the designed GUI and description of different parts, GUI is presented in figure 22.

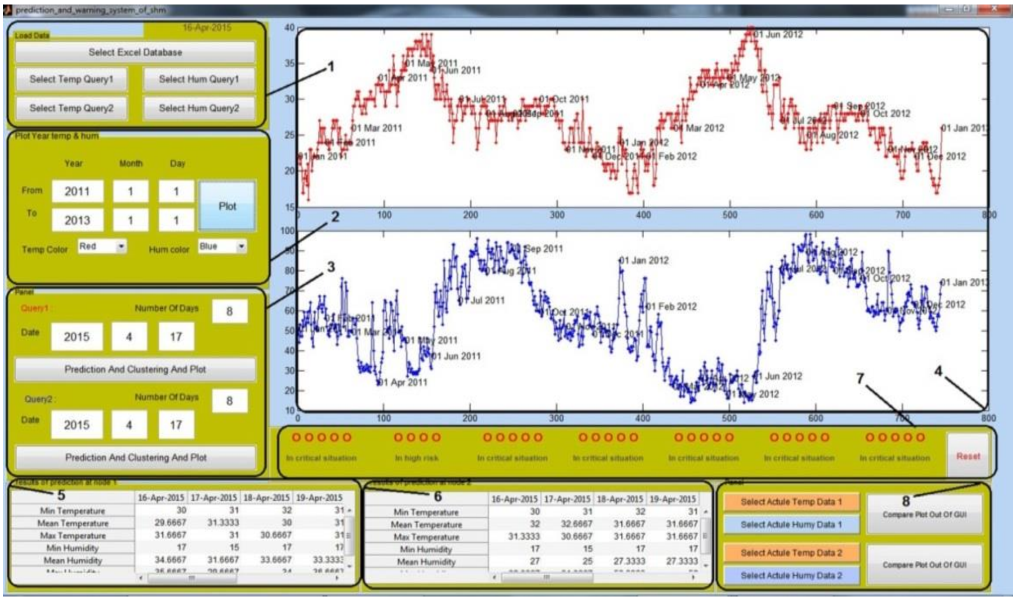

Figure 22. An overview of GUI for temperature and humidity prediction section.

Section 1: in this section, the files containing the database information and queries 1 and 2 each of which containing 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 the historical profile of the bridges and climatic conditions of its location in a specific period).
Section 3: this section provides the user to enter his/her desired date for prediction based on the data for the first or second node and also enables the 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 the user's desired time period.
Section 5: this section displays the average, maximum, and minimum values for humidity and temperature in node 1.
Section 6: this section displays the average, maximum, and minimum values for humidity and temperature in node 2.
Section 7: this section displays the alarm level and the possibility of resetting it.
Section 8: this section provides the possibility of making a visual comparison between the predicted values for 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 the 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 a fuzzy analysis on the 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 below the predicted values for temperature and humidity for each given day. In addition, the ability of resetting these levels for the next predictions is also embedded in GUI.
The specifications of the designed Mamdani FIS for the alarm system are as follows:

- **1-First input: temperature (refer to Figure 23)**
- **Three membership functions: low, medium, high**
- **Input range: between 0 and 50 degrees**

2- Second input: humidity (refer to Figure 24)
- **Three membership functions: low, medium, high**
- **Input range: between 0% to 100% (%RH)**

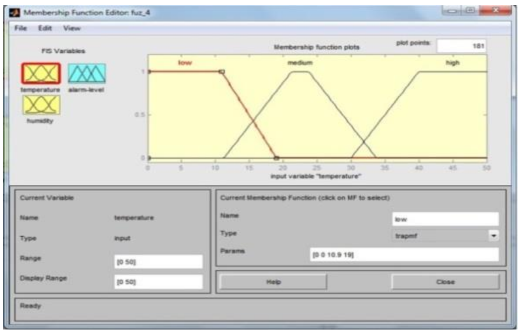

Figure 23. Membership functions for temperature (input) and its range.

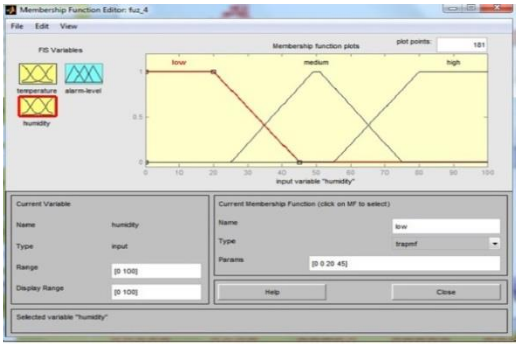

Figure 24. Membership functions for humidity (input) and its range.

3- Output: Alarm level (refer to Figure 25)

- **Five membership functions: one, two, three, four, five**
- **Output range: between 0 and 5**

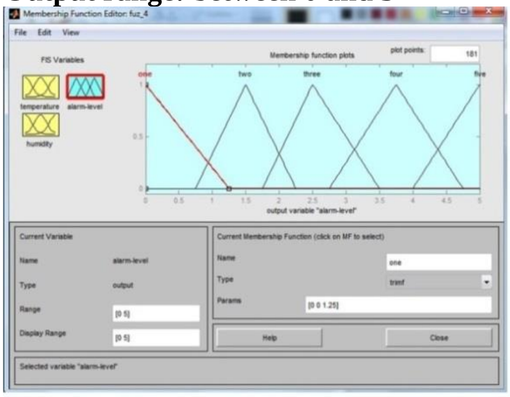

Figure 25. Membership functions for Alarm level (output) and its range

There are 9 rules for the above FIS system, as follow:

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)

The weighted average method is used for de-fuzzyfication. The details of the FIS performance in determining the alarm level are as figure 26.

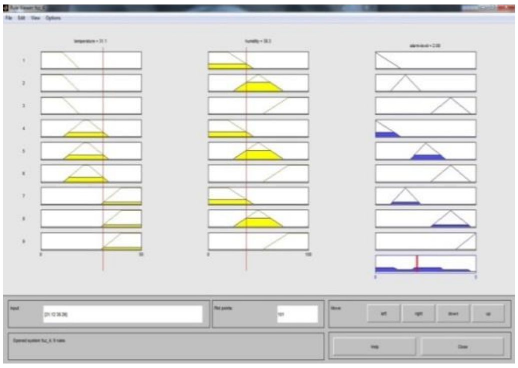

Figure 26. Rule-viewer of designed FIS.

In the end, representation of the above system as Surface will be like figure 27.

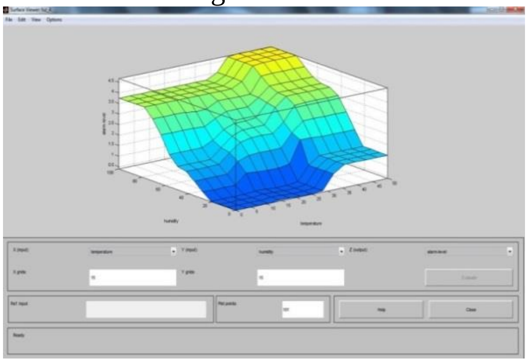

Figure 27. Surface view of FIS and summarization of effects of temperature and humidity (inputs) on alarm level (output).

The system with the above specifications determines an alarm level for the predicted values based on the details of the inputs and outputs 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, the bridge maintenance personnel can perform the proactive maintenance operations with greater efficiency and before temperature and humidity values reach the critical conditions in order to prevent the growth and spread of the damage and to fix it with minimum cost when the damage is still in its initial stages. At the end of the third section of this 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 the actual data is provided in our SHM system. Figures 28 and 29 show the comparison of the predicted temperature and humidity values with the actual logged values in node 1 and node 2, respectively.

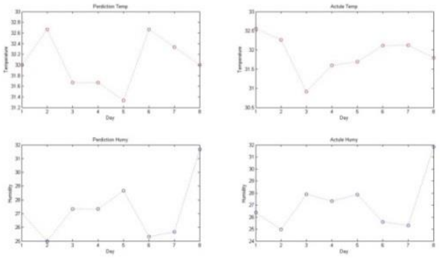

Figure 28. Comparison of predicted temperature and humidity values in node 1 with actual logged values.

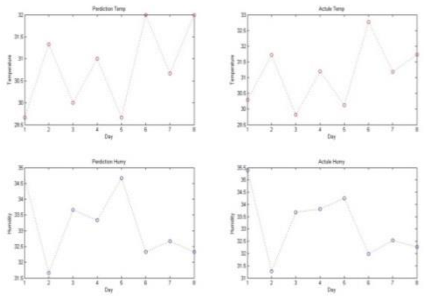

Figure 29. Comparison of predicted temperature and humidity values in node 2 with actual logged values.

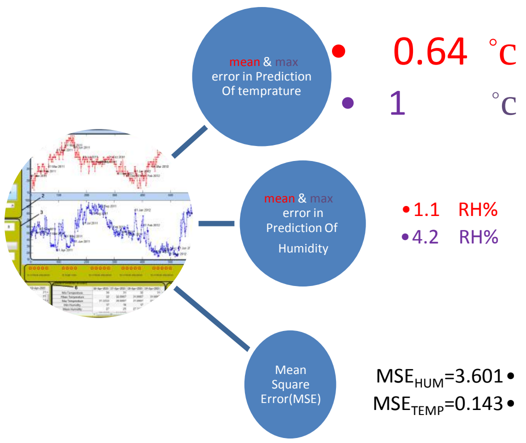

Figure 30. Maximum error, mean error, and MSE values for temperature and humidity predicted by proposed system.

The calculations showed that the mean squared error (MSE) of the prediction was about 0.143 for temperature and 3.601 for humidity. The results obtained are summarized in figure 30.

3.3. Examples of the application of proposed monitoring system

In this section, we present some examples of the applications of the multi-level alarm system discussed in the previous section. As mentioned earlier, this system contains 5 levels of alarm for temperature, humidity, and displacement based on fuzzy definition of critical thresholds. (The exact details of the alarm levels were presented in the previous section).

- ALARM-LEVEL-2: removing garbage and debris from the road surface and drainage system in response to alarm level 2 regarding humidity of the nodes located on the surface and edge of drainage system (as an example, refer to Figure 31).

Figure 31. Removing garbage and debris from road surface and drainage system to address alarm [5].

- ALARM-LEVEL-3: Pressure washing the drainage system in response to level 3 regarding the increased humidity in the node located at the throat of drainage system, which indicate that it is clogged (as an example, refer to Figure 32).

Figure 32. Pressure washing the drainage system [5].

- ALARM-LEVEL-2: Filling the cracks in the initial stages of their formation in response to alarm level 2 regarding the temperature of the node located on the deck surface area (as an example, refer to Figure 33).

Figure 33. Filling cracks in initial stages of their formation [5].

4. Conclusion

In this study, a system with multiple functions was designed, implemented, and simulated for monitoring the structural health of a medium-sized assumed bridge (length of 50 m, height of 10 m, and with 6 piers) with the use of wireless sensor networks. The proposed SHM system monitors the temperature and humidity parameters in two points of the bridge deck.

To monitor the temperature and humidity, sensor nodes include two end nodes both of which have the LM35 sensor for temperature and HIH4000 sensor for humidity and a coordinator node in which the 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; the mean squared error in the calculation of temperature and humidity values were (1.651 degrees) and (2.192 degrees), respectively. The data for a wired SHT11 digital sensor was used as the reference and standard for measuring the errors.

In this study, the proposed SHM monitoring system was equipped with a novel method of using data mining techniques (KNN algorithm) on the temperature and humidity data for the 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 the fuzzy analysis on the predicted values for temperature and humidity to move toward the 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 the temperature and humidity values were (1 degree) and (4.2 degrees), respectively; the mean squared error in the prediction of the temperature and humidity values were (0.143 degree) and (3.601 degrees), respectively. The data for the monitoring system was used as the reference and standard for measuring the errors of the prediction section of MATLAB program.

In the end, given the accuracy and reliability of the assessments, the analysis results, and the much lower costs of this system in terms of the initial equipment and maintenance (due to the simplicity of its structure), the proposed SHM system (which at this stage is still a combination of hardware and simulation) can be used for along-term and real-time monitoring of the medium-sized to the 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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نشریه هوش مصنوعی و داده کاوی

مطالعه ی موردی در رابطه با کاربرد منطق فازی و داده‌کاوی در نظارت بر سلامت سازه

سامان شورابی ثانی*

دانشکده ی مهندسی برق و کامپیوتر، دانشگاه حکیم سبزواری، سبزوار، ایران.

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چکیده:

در این پژوهش یک سیستم نظارت بر سلامت سازه[1] برای قسمت عرشه‌ی پل با قابلیت پیش‌بینی انواع مختلف آسیب‌های احتمالی وارد بر این بخش از سازه‌ی پل که مبتنی بر اندازه‌گیری مقادیر دما و رطوبت نسبی است با استفاده از شبکه‌های حس‌گر بی‌سیم طراحی می‌شود و سپس پیاده‌سازی شده و مورد ارزیابی قرار می‌گیرد. یک مدل مقیاس‌بندی شده از پل‌های رایج امروزی(به طول ۵۰ متر و ارتفاع ۱۰ متر که دارای ۲ عدد پایه است) به عنوان مطالعه‌ی موردی در این مقاله مدنظر قرار داده می‌شود. داده‌های جمع آوری شده توسط سیستم-شامل مقادیر دما و رطوبت نسبی- با استفاده از یک نرم افزار طراحی شده مبتنی برLABVIEW مورد ارزیابی و ذخیره‌سازی قرار می‌گیرند. سیستم نظارت بر سلامت سازه پیشنهادی از طریق تکنیک‌های ویژه‌ی داده‌کاوی بر روی بانک اطلاعاتی مربوط به پروفایل شرایط آب و هوایی چند سال گذشته‌ی مکان قرارگیری پل، ارتقا داده شده است و می‌تواند مکان وقوع و شدت آسیب احتمالی وارد بر عرشه‌ی پل را پیش‌بینی کند. داده‌ها و نتایج به دست آمده در تمام موارد مطرح شده به طور کامل مورد ارزیابی و آزمون قرار گرفتند. نتایج حاصل نشان می‌دهد که سیستم پیشنهادی صلاحیت لازم و کافی برای اهداف نظارت بر سلامت سازه در یک پل فرضی نمونه را دارد.

کلمات کلیدی: نظارت بر سلامت سازه، شبکه‌های حس‌گر بی‌سیم، نگهداری و تعمیرات بهره‌ور فراگیر، تکنیک‌های داده‌کاوی و استنتاج فازی.

[1] Structural Health Monitoring(SHM)