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Survey on IoT based Bridge Health Monitoring Systems

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***Abstract*: Infrastructure is one of the most crucial resources of a nation and is important for the socio-economic growth of the society. Bridges are the most vulnerable structures and need constant checking. There are only checks at specific intervals. During these checks if there is any major deformity which can cause irreversible damage to the bridge there is a huge risk of both life and property. Bridges need to be regularly checked for any damage and deterioration. Regular and efficient auditing is very important. In this paper, we have discussed our findings on various techniques used in Auditing of the health of Bridges.**

***Keywords*: Bridges, IoT, Automation, Embedded Systems.**

1. Introduction

In developing countries, bridges are necessary for their economic growth. Construction of bridges is a complex procedure and requires investment of time, money and energy on a large scale. India is a highly populated country and bridges have become an integral part of transportation which has fueled the growing economy. Bridges have helped making transportation over water bodies easier and have also helped ease out traffic by allowing a direct route over the ever-growing city traffic. Thus, be it pedestrian bridges or for the transportation of vehicles, bridges play an intrinsic role in today's world.

Bridges are one of the most vulnerable infrastructures as they are constantly affected by external factors. Factors such as friction, the load on the bridge, temperature, cracks, vibrations, the age of the bridge, etc play a significant role in the health of the bridge. These factors can lead to the collapsing of bridges and cause damage to life and property. Bridges need to be regularly checked for any damage and deterioration. Regular and efficient auditing is very important.

However, recently in Mumbai two bridges collapsed causing a tremendous harm to human life. It was found out that the auditing of those bridges wasn't done properly and they weren't maintained to the optimum level. Also, there is always a room for human error. Thus, it is necessary to devise an automated system which will constantly monitor the health of bridges efficiently and give proper warning signals whenever necessary. This monitoring system will be Internet of Things (IoT) based.

We have studied various papers which have implemented such IoT based automated bridge health monitoring systems and discussed them in this paper. This will help one gain a comprehensive idea of all the different types of systems used and can help one develop an efficient system based on the previously used systems.

2. Literature Survey

Eusebiu Pruteanu and Petru Gabriel, "Intelligent measuring system using network wireless sensors for structural diagnostics", International Conference on Control Systems and Computer Science (CSCS), 2019

Eusebiu Pruteanu and Petru Gabriel [1] have designed a system that monitors Structural Tension under external environmental load. The proposed System is a reliable system for measurement and diagnostics to predict structural failures through non-destructive diagnostic procedures. A wireless sensor network is implemented based on smart sensors with built in microprocessors and wireless communication. The system makes use of lamb waves and piezo-wafer active sensors. It integrates Structural Diagnostics and Analysis with non-destructive testing methods and Measurement Systems, Intelligent Materials, Data Transmission and Signal Processing [1].

Mahmud, Md Anam, et al. "A complete Internet of Things (IoT) platform for Structural Health Monitoring (SHM)." Internet of Things (WF-IoT), 2018 IEEE 4th World Forum on. IEEE, 2018.

Md Anam [2] proposes a complete IoT SHM platform that consists of a Raspberry Pi, an analog to digital converter (ADC) MCP3008, and a Wi-Fi module for wireless communication. Piezoelectric (PZT) sensors and they were used to collect the data from the structure. The raspberry pi performs the necessary calculations to determine the SHM status using a proposed mathematical model to determine the damage's location and size if any. The All the data is pushed to the Internet filter using ThingWorx platform [2].

Xiangxing Li, Hongmei Cui, Benniu Zhang and Can Yuan, "Experimental Study of a Structural Health Monitoring Method Based on Piezoelectric Element Array", IEEE 2017

Xiangxing Li, Hongmei Cui, Benniu Zhang and Can Yuan [3] have published this paper proposing a Structural Health Monitoring Method and System based on Piezoelectric Element

Array. It uses piezoelectric ceramic slices which is adhered to the surface of the structures to detect small mechanical vibration. The use of Piezoelectric Elements makes the system more stable and improves its performance. Piezoelectric material has the ability to convert mechanical energy to electrical energy. and vice versa. It can be used as sensors and actuators in smart systems. Piezoelectric materials have a large linear measurement range, fast response, high energy conversion rate and good stability [3].

Mahmud, Md Anam, et al. "Signal processing techniques for IoT-based structural health monitoring." Microelectronics (ICM), 2017 29th International Conference on. IEEE, 2017

Md Anam [4] has proposed a Structural Health Monitoring (SHM) with Internet of Things (IoT) can help improving security and safety. However, efficient signal processing for IoT is a challenge. In this paper, a signal processing based SHM is proposed where a simple Butterworth filter was used to remove noises. Cross-Correlation was used for damage detection. If there was any damage found, using a mathematical model, damage size and location were determined. After analyzing the experimental data, error found in damage localization is 2.9% and error in determining damage size is 3.344%. Since the whole algorithm does not associate with complex mathematical calculations, this system can be used for low-cost distributed system for SHM.

Jin-Lian Lee, Yaw-Yauan Tyan, Ming-Hui Wen and Yun-Wu Wu, “Development of an IoT-based Bridge Safety Monitoring System”, IEEE International Conference on Applied System Innovation (IEEE-ICASI), 2017

A comprehensive IoT based system [5] is developed and proposed in this paper by Jin-Lian Lee, Yaw-Yauan Tyan, Ming-Hui Wen and Yun-Wu Wu. The system comprises of monitoring units and photovoltaic units. It provides a solution to the problems of conventional systems for bridge safety management and control by collecting environmental data of the bridge in real time and transmitting the data to mobile devices of the bridge safety management staff. An IoT based Bridge Health Monitoring System is developed. The System comprises of Monitoring Devices installed in Bridge Environment, Communication Devices connecting the Bridge Monitoring Devices and the cloud-based server, a dynamic database that stores the bridge condition data and a cloud-server that calculates and analyses data transmitted from the monitoring devices.

Pooja Krishnath Patil; S. R. Patil, “Structural health monitoring system using WSN for bridges” 2017 International Conference on Intelligent Computing and Control Systems (ICICCS)

S. R. Patil [6] has proposed a Structural health monitoring system which is used for measuring the key parameter of the structural and environmental conditions on a continuous base at real- time. For bridges and dam application, wireless sensor measures the acceleration, tilting angle of bridge pillar and water level. The wireless sensor network is used in industry, urban terrain tracking and civil structure monitoring, security and surveillance, smart buildings etc. The sensor nodes in a sensor network are capable of collecting bridge or dam information and communicate with other connected nodes in the network. It is also capable of performing some processing part. Wireless sensor nodes are consisting microcontroller, transceiver, power management unit (power source), and one or more sensors. For bridge application they have used accelerometer sensors and ultrasonic sensor. The main aim of this project is to minimize the structural damages and prevent the life and property [6].

Zrelli, Amira, Hacen Khlaifi, and Tahar Ezzedine. "Application of damage detection for bridge health monitoring." Internet of Things, Embedded Systems and Communications (IINTEC), 2017 International Conference on. IEEE, 2017.

Amira Zrelli [7] has proposed a bridge monitoring system with the help of wireless sensor network. Environmental monitoring applications have a crucial importance for the company as a whole. The network of a without son sensor is the adopted technology to reach this goal. So, it should be capable to quickly provide, the information concerning the physical phenomena occurring in its environment. The principle objective of this system is to locate and to detect damages in bridges by the use of wireless sensor network. Internet of things presents a solution for damage in bridge of health monitoring [7].

Chih-Chyau Yang, et al. "A rugged sensor system for real-time bridge safety monitoring in Taiwan." Sensors Applications Symposium (SAS), 2016 IEEE. IEEE, 2016

Chih-Chyau [8] has proposed a rugged sensor system with algorithm to detect the bridge scour in real time. The presented rugged sensor system consists of under-water sensor nodes with the wired Ethernet communication protocol, a PoE switch and a data logger. The proposed under- water sensor node is implemented with two stacked octagon PCBs and enclosed in a steel hollow ball and then setup in the steel cage. The under-water sensor node adopts the vibration sensing mechanism to detect the bridge scour by using the accelerometer sensor. The presented sensor system is setup in Min-Chu Bridge in the middle of Taiwan to monitor the bridge scour.

Chih-Hsing Lin, Ssu-Ying Chen, Chih-Chyau Yang, Chien-Ming Wu, Chun-Ming Huang, Chih-Ting Kuo and Yu-Da Huang, “Structural Health Monitoring of Bridges Using Cost-Effective 1-axis Accelerometers”, IEEE International Conference on Automation and Logistics, 2014

In this paper, Chih-Hsing Lin, Ssu-Ying Chen, Chih-Chyau Yang, Chien-Ming Wu, Chun-Ming Huang, Chih-Ting Kuo and Yu-Da Huang used three 1-axis accelerometers instead of one 3-axis accelerometer for monitoring vibrations of a bridge structure. The paper states that it is 64.3% more cost effective while the number of sensors is optimal with only 0.37% error in terms of sample rate [9 accelerometers instead of one 3-axis accelerometer for monitoring vibrations of a bridge structure.

Table 1
Comparison of structural health monitoring systems

S. No.	Publication / Year / Author	Work done / Algorithm / Concept / Idea presented in the paper	Observation
1	Intelligent measuring system using network wireless sensors for structural diagnostics by Eusebiu Pruteanu and Petru Gabriel 2019	In this Structural Health Monitoring System, structural tension under external environmental loads is monitored. The proposed SHM system is a reliable system for measurement and diagnostics to predict structural failures through non-destructive diagnostic procedures.	A wireless sensor network is implemented based on smart sensors with built in microprocessors and wireless communication. The system makes use of lamb waves and piezo-wafer active sensors (PWASs). It integrates Structural Diagnostics and Analysis with non-destructive testing methods and Measurement Systems, Intelligent Materials, Data Transmission and Signal Processing.
2	Mahmud, Md Anam, et al. "A complete Internet of Things (IoT) platform for Structural Health Monitoring (SHM)." Internet of Things (WF-IoT), 2018 IEEE 4th World Forum on. IEEE, 2018	The platform consists of a Raspberry Pi, an analog to digital converter (ADC) MCP3008, and a Wi-Fi module for wireless communication. Piezoelectric (PZT) sensors to collect the data from the structure.	It is a complex and expensive system to maintain
3	Xiangxing Li, Hongmei Cui, Benniu Zhang and Can Yuan, "Experimental Study of a Structural Health Monitoring Method Based on Piezoelectric Element Array", IEEE 2017	A Structural Health Monitoring Method and System based on Piezoelectric Element Array is proposed in this paper. It uses piezoelectric ceramic slices which is adhered to the surface of the structures to detect small mechanical vibration. The use of Piezoelectric Elements makes the system more stable and improves its performance.	Piezoelectric material has the ability to convert mechanical energy to electrical energy. and vice versa. It can be used as sensors and actuators in smart systems. Piezoelectric materials have a large linear measurement range, fast response, high energy conversion rate and good stability.
4	Mahmud, Md Anam, et al. "Signal processing techniques for IoT-based structural health monitoring." Microelectronics (ICM), 2017 29th International Conference on. IEEE, 2017	A signal processing based SHM is proposed where a simple Butterworth filter was used to remove noises. Cross- Correlation was used for damage detection. If there was any damage found, using a mathematical model, damage size and location were determined.	This system has a reliability issue.
5	Jin-Lian Lee, Yaw-Yauan Tyan, Ming-Hui Wen and Yun-Wu Wu, "Development of an IoT-based Bridge Safety Monitoring System", IEEE International Conference on Applied System Innovation (IEEE-ICASI), 2017	A comprehensive IoT based system is developed which comprises of monitoring units and photovoltaic units. It provides a solution to the problems of conventional systems for bridge safety management and control by collecting environmental data of the bridge in real time and transmitting the data to mobile devices of the bridge safety management staff.	An IoT based Bridge Safety Monitoring System is developed. The System comprises of Monitoring Devices installed in Bridge Environment, Communication Devices connecting the Bridge Monitoring Devices and the cloud-based server, a dynamic database that stores the bridge condition data and a cloud-server that calculates and analyzes data transmitted from the monitoring devices.
6	Pooja Krishnath Patil; S. R. Patil, "Structural health monitoring system using WSN for bridges" 2017 International Conference on Intelligent Computing and Control Systems (ICICCS), 2017	Wireless sensors to monitor physical or environmental condition like pressure, level of water, acceleration etc. For bridges and dam application, wireless sensor measures the acceleration, tilting angle of bridge pillar and water level.	Its makes use of lot of sensors for bridge health monitoring which makes the system complex and expensive.
7	Zrelli, Amira, Hacen Khlaifi, and Tahar Ezzedine. "Application of damage detection for bridge health monitoring." Internet of Things, Embedded Systems and Communications (IINTEC), 2017 International Conference on. IEEE, 2017	The hardware design of the system adopts the way of wireless sensor network. Open source software like Xamp Apache, Arduino IDE, Contiki for the user application.	Health of the bridge is monitored by only considering vibrations.
8	Chih-Chyau Yang, et al. "A rugged sensor system for real-time bridge safety monitoring in Taiwan." Sensors Applications Symposium (SAS), 2016 IEEE. IEEE, 2016	This paper presents a system that is responsible to trace the scouring depth of bridge pile foundation. The rugged sensor system can detect the bridge scour with a proposed scour detection algorithm in real time.	This system detects only the scouring depth and is applicable only for bridges standing on water bodies.
9	Chih-Hsing Lin, Ssu-Ying Chen, Chih-Chyau Yang, Chien-Ming Wu, Chun-Ming Huang, Chih-Ting Kuo and Yu-Da Huang, "Structural Health Monitoring of Bridges Using Cost-Effective 1-axis Accelerometers", IEEE International Conference on Automation and Logistics, 2014	The paper proposes usage of three 1-axis accelerometers instead of one 3-axis accelerometer for monitoring vibrations of a bridge structure. The paper states that it is 64.3% more cost effective while the number of sensors is optimal with only 0.37% error in terms of sample rate.	The proposed system makes use of three 1-axis accelerometers, microprocessors, Analog to Digital Convertors and Data Logger. The proposal of using three 1-axis accelerometers instead of one 3-axis accelerometer makes it much more cost effective and thus, more efficient.
10	Baoping Cheng, Ming Yang, Weiguo Di and Yuebo Wang, "Bridge Monitoring System Based on Distribution Network Sensor", IEEE International Conference on Automation and Logistics, 2007	Deck Deflection is a parameter taken into account while evaluating the healthy status of a bridge. A Photoelectric Liquid Level Deflection Sensor is proposed which is economic, has better automaticity and higher precision for long distance and real-time online monitoring.	Change of Bridge Deck Deflection is obtained using network of Photoelectric Liquid Level Deflection (PLLD) Sensors. Deck Deck Deflection is an important parameter to be tracked when it comes to Bridges. Keeping Deck Deflection in check and implementing preventive measures on the damage can save the bridge from grave dangers.

The paper states that it is 64.3% more cost effective while the number of sensors is optimal with only 0.37% error in terms of sample rate [9].

Baoping Cheng, Ming Yang, Weiguo Di and Yuebo Wang, "Bridge Monitoring System Based on Distribution Network Sensor", IEEE International Conference on Automation and Logistics, 2007.

In this paper, Baoping Cheng, Ming Yang, Weiguo Di and Yuebo Wang have suggested the use of Photoelectric Liquid Level Deflection (PLLD) Sensors to measure the change of Bridge Deck Deflection. Deck Deflection is a parameter taken into account while evaluating the healthy status of a bridge. A Photoelectric Liquid Level Deflection Sensor is proposed which is economic. The System comprises of water containers set at the pier of the bridge. Each container is connected with some deflection sensor. The deflection sensor is composed liquid conduction, Optical sensor and Data Acquisition part. The proposed system has shown credible and stable performance and high precision and can achieve long period remote online automatic monitoring. The system has been applied in Xiaogou Bridge of the XinYuan highway in ShanXi province for testing [10].

3. Structural audit systems

A. *Structural Audit and Redevelopment of Shivaji Bridge*

Pinkesh Machhi, Rishikesh Nandavadekar, Indrajeet Shah & Abdul Moin Siddiqui - graduate students from the Department of Civil Engineering Genba Sopanrao Moze College of Engineering, Pune did a structural audit of the Shivaji Bridge in the Pune city which completed its construction in the year 1921. This was done by checking certain conditions. This paper discusses the basic structural auditing rules and techniques. Any bridge that has passed the age of 30 years has to get audited. This auditing involves mainly visual inspection. Visual inspection involves,

- Checking any inconsistencies in the proposed and the actual design.
- Checking for any sort of structural damage or major alterations in the bridge.
- Observing the bridges overall health - checking for any visual deformities like cracks.
- Identifying all the major changes throughout the year and recording all the details.

Auditing process doesn't stop there. Once the inspector finds out any problems, they have to propose remedial measures for maintaining the quality of the bridge. These remedial measures may include replacement of parts, repair or several other techniques. The measures are implemented by the designated people. This prevents the bridge from deterioration. Now that the bridge has grown weak there are different ideas proposed to make a new, much sturdy bridge. There are a lot of different types of bridges proposed and their specification is given.

B. *Structural Audit of bridges*

P. S. Jadhav, R. S. Chavan, G. K. Mohite, R. D. Gosavi and P. S. Shinde published this paper with a comprehensive study of Structural Auditing techniques. The paper tries to create awareness among civil engineers and users of public bridges towards the health examination of bridges in India. It describes the following techniques of structural audit:

- Visual Observations
  - General information of the building
  - Structural System of the building
  - Additions or Alterations in the building
- Destructive Testing
  - Core cutter test
- Non-destructive Testing
  - Rebound Hammer Test
  - Pulse Echo Method
  - Impact Echo Method
  - Ultrasonic Pulse Velocity Method

The paper provides a comprehensive study of the auditing process of inspection of bridges. It encompasses all procedures carried out on different types of bridges. It refers to other papers in this domain including the above-mentioned paper on Shivaji Bridge. The paper thus covers techniques used in India for Structural Auditing of Bridges.

4. Conclusion

An in-depth study is carried out about Bridge Health Auditing and various Automation Systems that are proposed and implemented in this field. The manual process of inspection of bridges that is carried out in India is described for different techniques and different types of bridges. Some of the Automation Systems proposed make use of IoT, Embedded Systems, SHM (Structural Health Monitoring) Systems and Distributed WSN (Wireless Sensor Networks). Automation of the auditing process will eliminate the scope of any human error in it. It will also improve the accuracy and increase the frequency of these inspections. Carrying out inspection audits regularly will help reduce the risk of dangerous accidents. All infrastructures especially Bridges are subject to constant corrosion which makes them vulnerable to degradation, thus making them prone to accidents. Such accidents on bridges can lead to loss of Human Life and Property. Thus, it is important to understand the need of Bridge Health and its Auditing Techniques.

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