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A Survey on Wireless Sensor Networks Based Structural Health Monitoring

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ABSTRACT

Structural health monitoring with the aid of wireless sensor networks has achieved analysis interest because of its capability to minimize the prices related to the implementation and maintenance of SHM systems. Structural health monitoring systems are used for systematic observation of vital infrastructure such as high rise buildings, bridges and stadiums and has the potential to enhance civilian structure life time and improve public safety. The high information assortment rate of the WSNs for SHMs cause distinctive network design challenges. This paper present a basic survey of SHM using WSNs outlining the algorithms utilized in physical harm investigation and localization, presenting network data flow methods and future systematic investigation directionsand network design relatedconcepts like network scalability, energy harvesting, processing of data are also discussed.

Key words: *Structural health monitoring, Types of sensors,network data flow methods, network scalability, energy harvesting.*

I. INTRODUCTION

Over the last decade wireless sensor networks have emerged as a powerful economical platform for connecting large networks of sensors. These networks have found many applications in health, military, business and industrial areas within which sensors distributed throughout a structure are used to analyse
the health of structure [1]-[2]. Traditionally SHM systems were designed using wired sensor networks, however less installation and maintenancecost, high reliability of WSN's have created them a compelling alternate platform [4]-[7]. The Significant price reductions of exploitation WSN's for SHM would modify their effective utilization in necessary public and personal infrastructure and increase the applications like short term health monitoring. In WSNs for SHM sensors are deployed at numerous locations through a structure. These sensors collect information regarding acceleration, surrounding vibration, load and stress at sampling frequencies of 100 hertz. Therefore the sensing and sampling rates and quantity of collected data are higher level those in other applications in WSN's and as a result , WSN's For SHM introduce challenges in design of network.Sensing element nodes transmit the detected data to the sink either directly or by forwarding every other's packets information collectively and process is critical for the detection and localization of structural damage and might happens in different locations such a s

nodes, cluster heads , and or central server depending upon the topology of structure. Typically damage detection require the comparison of the structure's present modal options to those related to the structure's undamaged state. Modal options of a structure are primarily represented by the mode shapes and natural vibration pattern for a given structure.

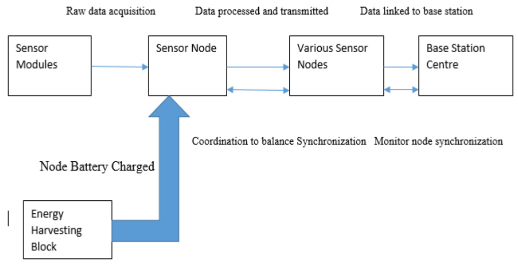

Figure a. Block diagram of SHM using WSN's

SHM has been deployed in crucial structures like aerial vehicles, ships, high rise buildings, dams, and bridges. Basically, these installations are wired; but, an increasing range of more number of WSN's.One of the first SHM was put in on the sound Bridge in 2007by a research team at the university of California in Berkeley. Sensors during this network collect close vibrations which are then routed from the origin device node to a centralized base station, the bottom station then processes the data and makes a fine decision on the structure's overall health.

Metrics	Wired Sensor Networks	Wireless Sensor Networks
Data Rate	High sensor data rate	Lower sensor data rate
Life Duration	Long, depends on hardware lifespan	Short, depends on node battery lifespan
Number of Sensors	Typically less due to installation of sensor difficulty.	Due to ease of sensor installation, typically higher
Connection Bandwidth	High bandwidth due to wired connection	Unreliable connection and limited bandwidth
Installation Time	Very long time consuming , real time examples takes several days	Short, real time examples takes a half an hour.
Price	Very High	Low
Sensor synchronization	Very high due to wired connections	Minimized due to wireless connection

Table 1. Distinguish between Wired and Wireless Sensor Networks

II. CHALLENGES IN WSN FOR SHM

In comparison to typical WSNs those designed for SHM face variety a singular challenges, specifically, WSNs for SHM nodes collect, process, and transmit large amount of data, sensor node densities are often high, and also the variety of hops from node to base station are often large, within the reviewed literature, real world deployments of SHM systems have had sensor sampling rate starting from a hundred to a thousand cps, node densities up to seventy nodes, and

Also the variety of hops to traverse the network starting from one to forty six. In existing SHM systems, delay necessities are low as terribly long delays can be acceptable for SHM systems observing a structure's long-term health .For example a 9 hour delay to gather, process and mixture knowledge at the base station are often acceptable. As long as data transmission is reliable .However, SHM systems designed to monitor a structure's health within the event related to earthquake or alternative natural disaster might need a far smaller delay. Although delay is mostly not a priority , synchronization of detector nodes is especially necessary in WSN's for SHM.Maximum node time synchronization errorshould be below a 120 microseconds otherwise damage detection and localization becomes not possible due to important mode shape errors. Lastly, the algorithm utilized in WSN's for SHM are additional advanced than those utilized in other WSN's.SHM algorithms are computationally advanced, could need the incorporation of data from other sensor nodes, and frequently needed centralized processing. Although the on the top of characteristics are comparatively distinctive when compared to most WSN's, WSN's for SHM have similar reliability and quality of service requirements. Data transmission is expected to be reliable and lost packets should be recovered through retransmission. Packet loss rates are often high in monitored structures as transmission could need wireless propagation through materials such as steel and concrete. Sensor nodes deployed on structures cherish bridges and wind turbines should stand up to severe atmospheric condition favorable rain and snow.WSNs for SHM have similar quality of service requirements to traditional WSNs except, as mentioned on the top of network time synchronization errors should be decreased.

III.SENSOR TYPES

The sensing and acquisition of the higher than parameters needs the employment of specific sensors. A summary of normally used sensors in SHM systems are as follows.

Accelerometers: Accelerometers used for SHM are either piezoelectric or spring-mass accelerometers. Electricity accelerometers are light-weight, small , and operate over wide acceleration and frequency ranges .on the opposite hand ,spring mass accelerometers are comparatively large and operate over a restricted vary of accelerations and frequencies.However,they are terribly sensitive to small accelerations and apply higher resolution than the electricity celerometers.The electricity measuring system mass that s coupled to a supporting base once the supporting base undergoes movement, the mass exert an inertia force on the crystal component. The exerted force on the crystal component. The exterted force produce produces a proportional electrical phenomenon on the crystal. Accelerometers will have sampling rates upwards of 100Hz.

Strain Sensors:

These sensors used for SHMis classified as piezo resistive or embedment strain gauge Based. Cement –based strain sensors are generally piezo resistive and are capable of measurement strain. These sensors generate signals with a low frequency less than 1Hz.Embedment strain gauges is used for measurement strains within concrete structures. An embedment gauge consists of an extended foil gauge about 100mm embedded in a polymer concrete block.Embedment Strain gauge are sensitive to environmental conditions such as the weather and, consequently, must be protected with enclosures.

Corrosion Sensors: These sensors usually live the amendment in resistance introduced by the erosion of the sensors corrosion wafer. These sensors usually determine a structure's overall corrosion [5].

Optical Fiber Sensors: The most general type of optical fiber sensor is the fiber Bragg Grating sensors[6], [7].These sensors can be used to measure parameters such as strain, temperature, pressure, and alternative parameters by changing a fiber so the number to be measured modulates the intensity, phase, polarization, and wavelength or transmit time of natural light in the fiber. Fiber-optic sensors are developed to measure strain and temperature at the same time with high accuracy using fiber Bragg gratings.

Out of the above listed sensor types, the most –generally used are piezoelectric accelerometers due to their low cost and nature of usage.As a result, maximum damage detection and localization techniques have been developed for these sensors.

Linear Voltage Differential Transducers (LVDT): LVDTs are used for displacement measuring and accommodates a hollow metallic casing within which a core or shaft, moves freely back and forth on the axis of measuring [8].The core is created of a magnetically semiconducting material and a coil assembly surrounds the metallic shaft. No voltage appears at the secondary windings once the core is equidistant between each secondary windings. However, when a displacement happens, the core moves, a differential voltage is evoked at the secondary output. The magnitude of the output voltage changes linearly with the magnitude of the core's displacement.

Network Scalability:

It is a network's ability to grow in size whereas continued to provide a high quality of service that meets application requirements with a suitable completeness. Guaranteeing measurability is particularly difficult in WSNs for SHM thanks to the Sheer amount of data assortment and transmission needed for effective harm detection and localization .As SHM systems are applied to larger and bigger structures the amount of hops and nodes required to observe the structure with most successfully will continue to increase. Even in a SHM systems for a constant size structure increasing node density, to a point can improve the system's ability to detect and localize damage. These parameters makes the improvement of scalable WSN's for SHM a priority basis. Parameters such as power consumption, time synchronization error, data transmission rate and data storage availability and processing algorithms affects a overall networks scalability. A network can successfully scale as long as the maximum network node time-synchronization remains below 120 microseconds [9].

In [10], a WSN for SHM is planned with one in all the objectives being the design of a scalable architecture. The proposed design consists of a base station and several other nodes controlled by the base station through a master-slave concept. This design improves measurability by guaranteeing a negligible time-synchronization error and reducing data transmission through the network. The time-synchronization error of network nodes is decreased through the utilization of a wireless synchronization module supported IEEE 802.15.4.In this module the server is chargeable for guaranteeing that network nodes have a negligible time synchronization error. In the proposed system nodes have a negligible time synchronization error. In the proposed system data transmission is decreased by only sending log files containing data concerning the sensors information keep on a given network node. Ifthe data is needed, it is requested from their sensor node by the base station using the information give in log file. As a consequence of solely sending log files, damagedetection and localization is not an ongoing process but one that is performed when the base station deems it necessary. In addition network nodes need ample storage such that sensed data is not discarded before to request from the base station

Energy Harvesting

Wireless sensor networks have been traditionally powered by batteries and as a result the limiting Factor in their total life duration has always been the battery life time. It was shown in [4] and [17] that the battery lifetime in WSNs for SHM can be extended upto 6-18 months depending on energy management techniques and the type of battery used, while the hardware can last many years. Consequently, research has been concentrated on maximizing battery life time through optimizing routing, sensor placement and scheduling. Cost reductions in energy harvesting has motivated to Research into the use of such systems in WSNs.

Energy Efficiency:

A common constraint two –faced by all WSNs is a maximum network lifespan due to the limited energy storage available for each sensor node. In WSNs for SHMit's typically not possible to interchange depleted batteries as sensors nodes are typically placed in difficult to access locations thhrought a structure. In addition, SHM applications require high sampling rates and consequently, an increase in on-node dataprocessing and transmission. Lastly, in comparison to typically WSN algorithms, SHM algorithms are complex, can

Require incorporation of data from other sensor nodes and are generally designed to be processed at a centralized location. These parameters makes energy efficiency an important consideration in WSNs for SHM.

Generally, energy efficiency can be improved in many ways. Radio optimization, data reduction , sleep schemes, energy-efficient routing and battery repletion have all been identified as techniques that can be used to extend the lifespan of WSN's [11].Out of the identified techniques, data reduction is particularly essential in WSNs for SHM due to the high volume of data collected and transmitted. Consequently, most research in increasing energy efficiency has been focused in this domain.

In WSNs for SHM important data reduction is achieved by distributing process throughout the network as critical centralizing process at the base station. Although this will increase

Node processor utilization as more cycles must be dedicated to complex computations. Important reductions within the quantity of data transmitted makes distributed process schemes very energy efficient. A comparison between a centralized processing scheme and two distributed processing schemes explained a vital reduction in the amount of data transmitted [12]. In the centralized processing scheme 667 bytes of traffic per second of network operation wastransmitted. While in the two distributed processing schemes 300 & 28 bytes of traffic per second of network operation were transmitted. These important reductions are achieved despite increases in the sampling rate of two cluster-based methods. In centralized scheme the sampling rate was only in 100Hz while in the tow cluster based schemes sampling rate was 560 and 1000Hz respectively.

IV. CLUSTERING AND DISTRIBUTED PROCESSING

A generally used technique in WSN design is clustering. In clustering sensors nodes are classified into clusters and every clusters includes a node selected because the cluster head (CH) .In a given cluster, all nodes, apart from the CH, will solely communicate with the Cluster head. The CH will communicate with all nodes in its cluster and near CHs.Cluster improves scalability simplifies routing, extends the networks life and conserves bandwidth [13].An important thought in WSNs for SHM is wherever in the networking processing is performed. In centralized data processing data is transmitted from the sensor nodes to a base station (BS) [14], [15].The BS processes the data and, supported the results, will assess the structure's overall health. In local processing the data is processed locally, a decision about structure made locally, and the decision is transmitted from the SN to the BS [16]. The overall network data flow for centralized, localized and cluster-based processing is illustrated in Figures**. i ,ii,iii.**

Centralized Processing

Centralized processing is the data processing technique generally used in WSNs for SHM.This technique is very simple to implement and minimizes the processing done at each of the sensor nodes. This method was used in the design of a WSN based SHM system for the main span and Golden Gate Bridge south tower [16].

The system uses a total 64 sensor nodes, had a total lifespan of 70 days and requires of 9 hours to complete a single round of data collection transmitting a total of 20MB of data .The high latency, big amount of transmitted data and short life span explains the issues with centralized processing in WSNs for SHM.The use of centralized process in SHM was also investigated in [15]. Sensor data was stored in nonvolatile memory storage till all memory was occupied when that data was transmitted from the sensor node to the base station wherever the processing is completed. This system was deployed on a model test structure and results indicated that even with a small low range of sensor nodes the data aggregation time was infeasible. The use of data compression to reduce the data aggregation time and the use of local processing to minimize the amount of data transmitted were two methods proposed to reduce overall data aggregation time. Total, centralized processing is the least complex processing technique and the easiest to implement. By only collecting data at each network node and routing it through the network on-node processingcan be reduced potentially extending the lifespanof each individual node and, consequently, the network. For bigger networks and for networks with poor link quality the energy reduction of on-node processing is reduced as nodes must spend a large number cycles collecting and routing data which could be avoided by performing some of the end-processing before to transmission. Centralized processing allows the usage of all damage detection and localization algorithms and, consequently, can avail of those that are most accurate for a given SHM application. The main limitation of centralized processing is high delay associated with long data-aggregation time. If delay is an issue, such as in application that monitors a structure's health in response to earthquake, centralized processing should be avoided .If delay is not an problem centralized processing can be used however the scalability of systems and structures greater than the Golden Gate Bridge needs to be evaluated.

Local Processing: One among the critical characteristics of SHM primarily based WSNs is that the great deal of information produced by network sensor nodes. This challenge motivated research into local processing techniques to scale back overall network traffic whereas maintaining an easy design. Due to a lack of a reference signal, local process renders general health detection strategies like technique of natural excitation-Eigen-system Realization Algorithm methodology [16].Damage detection algorithmic rule that has been investigated in the literature is that the autoregressive-autoregressive exogenous (AX-ARX) methodology [16].This methodology uses pattern recognition to match the structures current data with the information collected at the start of the structure's period of time. Through this comparison, each sensor calculates a damage sensitivity coefficient which is then used to notice, localize and quantify the damage of structures.

The viability of this algorithmic rule was tested in the simulation of a steel frame structure and it had been found that the damage detection and localization methodology was effective. An advantage of this methodology over cluster-based process is that it improves network strength.

By fully localizing processing, the network is formed resilient against cases where an vital node, Such as cluster-head, fails and leads to the loss of property for that entire cluster. Overall, local processing moves the complexity of damage detection and localization from the base station to the node itself. This improves network resiliency and greatly reduces the quantity of transmitted data

An improvement in on-node processing that will probably cause decrease in node time period.

The main limitation of local processing is that the damage detection and localization techniques which will be used without input from alternative nodes is limited and these techniques, such a AR-ARX ,tend to be less accuracy then such as NExT-ERA algorithm[20].

Cluster –Based Processing: Cluster –based process combines components of centralized and local processing to improve total network performance. By distributing the processing between every sensor node and also the cluster-head, the number of data transmitted through the network is reduced as compared to centralized process and also the amount of processing done at every of the SNs reduced in comparison to distributed processing .In general, the first objective of using cluster-based processing is to decrease overall network energyconsumption and improve the measure of scalability. Cluster-based process permits the usage of damage detection techniques that can't be used in local processing. The AR-ARX techniques has been applied in cluster –based processing systems, additionally to the distributed processing systems as mentioned above.

In [21], a WSN-based SHM system was planned supplements the AR-ARX method with the random decrement method [19] and the principle part analysis method [18] to reduce overall energy consumption. The random decrement technique compresses the data received at the sensor node by averaging a more number of time segments together into a small average segment of time. The compressed data is then transferred from every of the sensor node to the CH. Before AR-ARX processing, principal part analysis is applied to the combined data set from every of the cluster nodes [18]. PCA extracts solely the principle parts from the input data set by sorting the eigenvalues of the variance matrix and then choosing the most important eigenvalues till a specified threshold is reached. At this threshold, it is assumed that the included Eigen values sufficiently depicts the general dataset. The AR-ARX technique is then applied to the post-processed dataset and a main decision concerning the structure's overall health is made. Figure iv represents the total algorithmic rule and wherever in the network the various processing loads are completed. Oneof the limitation of using PCA technique is that it can increase overall energy consumption if the detector placements within the network and cluster not observed to be properly optimized. Consequently, genetic algorithms were not converge on a near –optimal resolution such total energy consumption was reduced in this method [21].

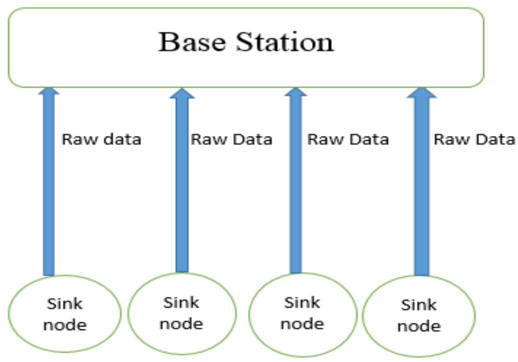

Figure i. Centralized Processing

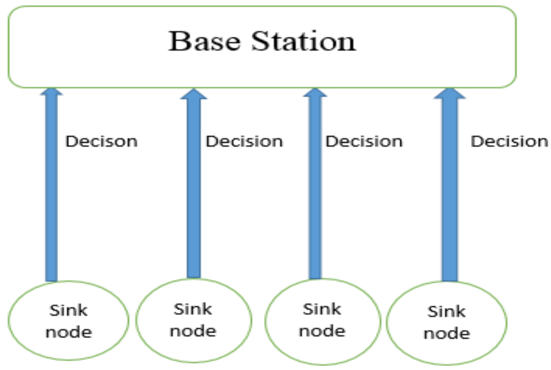

Figure ii. Local Processing

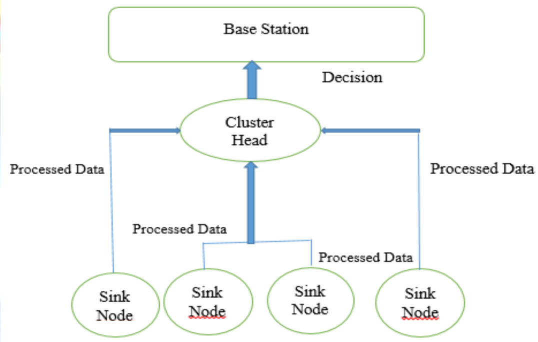

Figure iii. Cluster –Based Processing

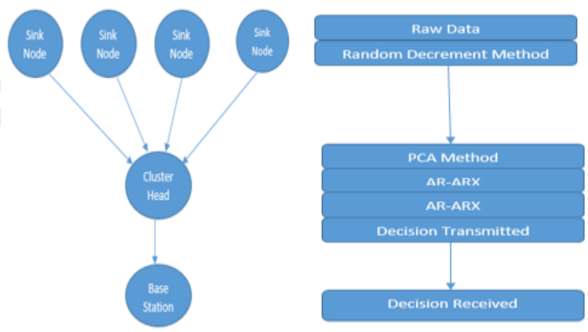

Figure iv. AR-ARX Method for Cluster based data processing

V.CONCLUSION

This surveypaper presented basic review of WSN based SHM systems. Background information with reference to structural health monitoring like common sensors used, brief idea of data processing algorithms used in SHM systems and generally measured factors like energy harvesting, Energy efficiency, network scalability and challenges in WSN for SHM are discussed.

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