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Energy Efficient Sensor Placement for Monitoring Structural Health

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Abstract: Wireless sensor networks (WSN) have large scope in structural health monitoring (SHM) applications such as monitoring strength of buildings, bridges, tunnels etc. But WSN based SHM need to face many challenges to get the same performance as its counterpart, the wired network. Placement of sensor nodes has an important role in WSN based SHM, as it needs to find a high quality position, so that it satisfies monitoring requirements and WSN challenges like energy efficiency, connectivity, fault tolerance and reliability. Monitoring quality could be obtained by sensor placement using effective independence method (SPEM) by maximizing fisher information matrix (placement quality indicator) which is used for sensor placement in Civil engineering structures, but it does not guarantee any WSN requirements. This paper therefore focuses on an energy efficient sensor placement method by improving SPEM, so that it improves the life time of sensor nodes or it minimizes the maximum energy used by the sensor for transmitting data to the base station and also ensures monitoring quality. The performance of the proposed placement method has been tested by MATLAB simulations and the result is compared with the sensor placement using effective independence method. This method obtains almost the same placement quality as that provided by using effective independence method, but with improvement in system life time.

Keywords: Wireless sensor network; Structural Health Monitoring; SPEM; FIM.

1. Introduction

A wireless sensor network (WSN) consists of many small sensor nodes or motes that can monitor physical or environmental condition such as pressure, temperature, vibration, sound, humidity and transmit the data wirelessly through the network to a main location called base station. Due to the advantage of easy deployment and cheap cost, wireless sensor network has many applications and structural health monitoring (SHM) is one of the main application.

Structural health monitoring (SHM) aims to monitor the behavior of a structure such as buildings, bridges and ensuring the structural integrity. In recent years the advancement in the WSN technology promises the low-cost wireless sensor nodes that have the capability to monitor a large structure and ensure its health. In order to achieve this goal we need to overcome many challenges such as energy constrained sensor nodes, bandwidth, communication reliability, etc.

In this paper, we aim to optimize the energy resource of WSN by optimum sensor nodes placement method without affecting the quality of monitoring. Civil engineers are placing sensor nodes to fulfill only monitoring requirements and it is good for wired network. But in wireless network, it is needed to fulfill requirements of computer engineering field such as energy optimization, bandwidth, reliability, fault tolerance etc.[1], [2].

In civil or structural engineering, many methods are available for placing sensor nodes. The one of the main methods are effective independence index (EFI) method [3], [4] and kinetic energy method [5]. In EFI method, based on the EFI value of each candidate position, sensor nodes are deployed. But in kinetic energy method, KE index value are used for placing sensor nodes. In this work, EFI method is used for the deployment of sensor nodes. After placing sensor nodes based on the value of effective index, the least effective independence index sensor nodes are changed to some special position so that optimum placement can be achieved.

The rest of the paper is organized in six parts. In part 2, related work is presented. In part 3, description about structural health monitoring system, its background, sensor placement methods and problem statement are presented. Proposed algorithm and simulation results are discussed in Section 4 and Section 5, respectively and Section 6 concludes the paper.

2. Related Work

In recent years, sensor networks have been experimented in many structural health monitoring applications. The structural health monitoring of Tin Kau Bridge [6] is one of the main example, but wired sensor networks dominated in this structure. Because of special advantages of wireless sensor network, researchers are more interested to develop a WSN based SHM. In Guangzhou New TV Tower [7], wireless based structural health monitoring system is used partially. An overview of SHM by using wireless sensors can be found in [8].

Many methods are there in wired network system for sensor placement. Effective independence method (EFI) proposed by Kammer [3] is one of the main approaches. But while deploying a WSN for SHM, the existing placement methods face many challenges like communication range, wireless bandwidth, fault tolerance etc. Sensor placement using EFI method (SPEM) [9], [10] is one of the main works for sensor placement in WSN based SHM, but this method also faces the challenges of WSN. So in this paper, optimal sensor placement for WSN based SHM application is discussed.

3. SHM System and Problem Statement

3.1 Background of the SHM

Structural health monitoring is used for ensuring the integrity of a structure. A reliable SHM system can help to predict the failure in building or structure through non- destructive procedure that can help economic and social benefits.

As the first step of SHM, Finite Element Model (FEM) of the structure is calculated. FEM is defined as a computer-based mathematical model for measuring the strength and behavior of a structure, such as displacement, vibration and load. The FEM model contains complete properties of a structure.

Mode shape [11] is another important term used in SHM. Each type of structure has a specific pattern of vibration at a specific frequency, called mode shape. It shows how a structure will vibrate and in what pattern. Mode shape matrix is denoted as Φ. Where Φ is shown as in equation (1), where each row indicates for mode shape measurement results from a particular sensor and here each M sensors have K type of mode shapes.

$$\Phi = \begin{bmatrix} \phi_{11} & \phi_{12} & \cdots & \phi_{1K} \\ \vdots & \vdots & \vdots & \vdots \\ \phi_{M1} & \phi_{M2} & \cdots & \phi_{MK} \end{bmatrix}_{M \times K} \tag{1}$$

Damage [11] is another parameter and it is defined as a significant change to the geometric properties of a structural system, such as changes captured frequencies and mode shapes.

3.2 Sensor Placement Using Effective Independence Method (SPEM)

Consider a structure of M candidate locations, which is given for monitoring. We have to find N locations to place sensor nodes, where N<<M, such that any changes that is occurring due to the structural health accurately identified. N places out of M feasible locations are selected by sensor placement using effective independence method (SPEM). The placement quality of sensors is indicated by determinant of Fisher Information Matrix (FIM), which is denote by Q as described in mathematical form shown as in equation (2).

$$\mathrm{Q} = \Phi^T . R^{-1} . \Phi \tag{2}$$

$$E_j = diag(\Phi . \mathrm{Q}^{-1} . \Phi^T) \tag{3}$$

Where R is the covariance matrix of noise and E_j is the effective independence value of j^{th} location. In SPEM, (M-N) feasible locations will be removed as described in the Algorithm 1.

Algorithm 1: SPEM

Let M is the number of candidate locations and N is the number of sensor nodes used for effective placement.

1. for i =1 : 1 : M-N
2. Compute E_j ;
3. Sort E_j ;
4. Remove last location (i.e., remove least E_j location From M location).
5. end

Output: N locations are selected from M total candidate location.

3.3 Objective of the Proposed Work

We have M feasible location to place N sensor nodes where N is less than M. Assume the base station or sink is placed at location S_0 and |Q| represent determinant of the FIM. Let the sensor nodes S= {S_1, S_2 . . . S_N} be placed in N locations, by removing M-N positions using SPEM algorithm so that |Q| will be maximized.

Let the maximum communication range of each sensors are R_{max} and each sensor nodes transmits its data to the base station in a shortest path. Let E_{max} is the maximum energy used by sensor in one round of data transmission.

The objective is to maximize |Q| and minimize E_{max}, i.e., the sensor placement quality and the sensors lifetime by minimizing maximum energy consumed by one sensor. i.e., we need to maximize the function |Q| / E_{max}.

4. Proposed Algorithm for Sensor Placement

By SPEM algorithm, we get N locations out of M feasible candidate locations, but this placement will affect many factors like energy consumption, connectivity, communication reliability and fault tolerance. So we developed an improved placement algorithm which is shown as Algorithm 2. In this algorithm sensors are placed based on EFI value and traffic of data through a path.

Algorithm 2: Proposed Algorithm

Let M is the number of feasible locations and N is the number of sensor nodes, where N<<M

1. Compute the N sensor node positions using Algorithm 1 (SPEM)
2. Compute the shortest path from all sensor nodes to sink where R_{max}, the maximum communication Range given for sensor node.
3. Find the node, which is using maximum energy in one round
4. Sort sensor nodes positions according to effective independence value, and remove last location.
5. Place the removed sensor nodes in a position, so that traffic through the nodes which is using maximum energy will be reduced.
6. Find the function $|Q|/E_{max}$ of new placement. If this function is more than previous one, then select it as new placement of sensors.
7. Continue from step 2, until we get good placement result.

5. Simulation Results

The simulation has been done using SAP (Structural Analysis Program) [12] and MATLAB simulator to evaluate the performance of the proposed method. For simulation we have considered a wall structure with 56 candidate positions and mode shape of the wall is calculated using SAP software. Using Algorithm 1, 20 sensor node positions are calculated using SPEM. Figure 1 represents the variation of percentage of quality indicator wise deleted positions from candidate sets in successive estimation using SPEM algorithm. Table 1 shows simulation parameters used for simulation.

Figure 1. Sensors deleted based on the Placement quality using SPEM

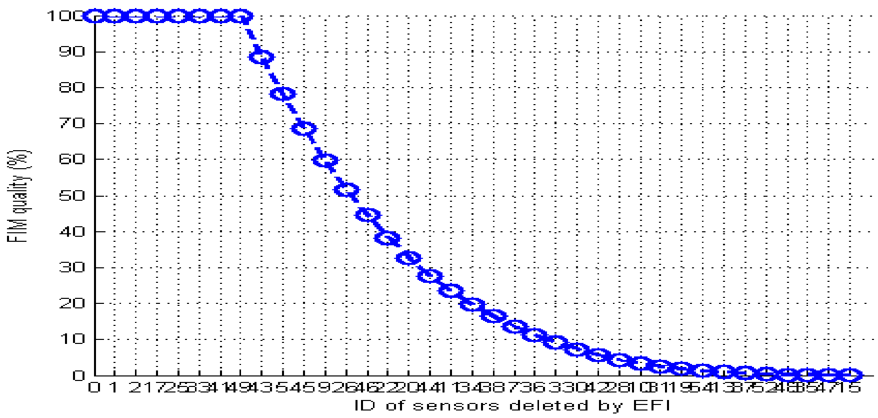

Table 1. Simulation Parameters value

Parameters used	Value
Number of sensor nodes, N	20
Number of candidate locations, M	56
Maximum communication range, Rmax	2m
Initial energy	0.5 J
Data packet length	4000 bits

Figure 2. Twenty sensor nodes are placed in a wall having 56 candidate locations and sink placed at (0, 0). Red line indicates the shortest path to sink for data transmission; (a) SPEM method are used for sensor placement; (b) sensor placed by proposed way and here two least effective sensor nodes placed at (0,6) & (0,2) are changed to (1, 1) & (2, 0) so that traffic through the nodes (0, 1) & (2, 1) will be reduced.

(a) Sensor placement using SPEM (b) Sensor placement using proposed one

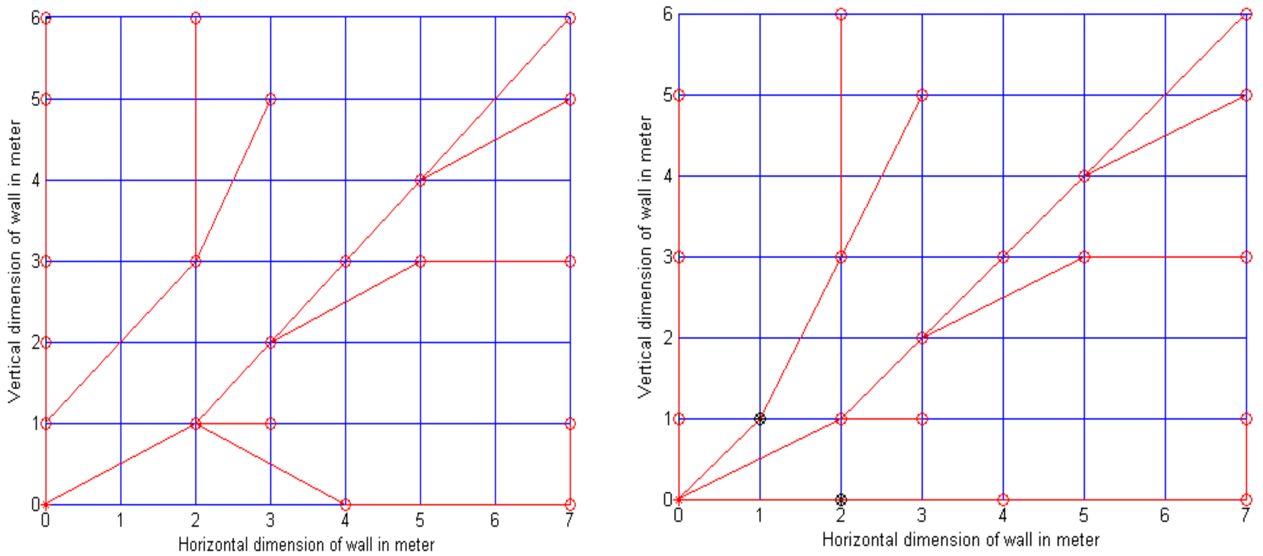

Table 2. Simulation results

Parameter	SPEM	Proposed One
Emax	0.0051 J	0.0037 J
|FIM|	63.0875	54.1972
$\frac{\|Q\|}{E\max}$	12370	14648
Number of round when first node dead	99	134

Figure 2 shows the placement of 20 sensor nodes on the wall structure having 56 candidate locations using SPEM and proposed method. In Table 2, simulation results of proposed algorithm with SPEM are compared and we can see that in proposed method the function |Q|/Emax improved considerably.

6. Conclusion

In this paper, the sensor placement problem is discussed for structural health monitoring system not only from civil engineering structures point of view, but also from computer science efficiency. In this work, we placed sensor nodes by maximizing fisher information matrix and by minimizing the maximum energy consumed by sensor. Through the simulation, we demonstrated that the proposed algorithm improves the lifetime of wireless sensor network without much affecting sensor placement quality. As a future work, we can consider placement of relay nodes based on the traffic awareness so that it may decrease energy consumption without affecting sensor placement quality.

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Conflicts of Interest

The authors declare no conflict of interest.

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