Research Article

The Nonuniform Node Configuration of Wireless Sensor Networks for Long-Span Bridge Health Monitoring

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1. Introduction

In recent years, a large number of long-span cable-supported bridges have been built throughout to fulfill the requirements of modern society for advanced transportation systems [1], for example, the Akashi Kaikyo Bridge with a main span of 1990 m in Japan, the Great Belt Bridge with a main span of 1624 m in Denmark, and the Runyang Suspension Bridge with a main span of 1490 m in China [2]. With the development of material and construction technology, bridges tend to light weight, low stiffness, and low damping, which make those bridges sensitive to dynamic loads. In order to verify new construction design assumptions, detect potential damage, and prevent catastrophic failure, structural health monitoring (SHM) is implemented on many existing or newly built bridges all over the world.

A typical SHM system includes three major components: a sensor system, a data processing system (including the data acquisition, transmission, and storage), and a health evaluation system [3]. The sensors are used to monitor structural status and environmental parameters, which provide necessary data for structural assessment. In the past few decades, numerous vibration-based damage detection approaches have been developed [4], which promote that the structural vibration monitoring is an important issue in SHM. Ideally, if all degree of freedoms (DOFs) of a bridge are placed with accelerometers, the dynamic response can be fully characterized. However, the high costs of data acquisition systems (including development, purchase, and maintenance costs for the accelerometers, as well as resource and communication costs) and accessibility limitations constrain in many cases the scale of the network. So, the optimization of accelerometer placement, which aims to select the optimal location of accelerometers so that the behavior of bridges can be well identified, is a key work prior to dynamic monitoring of bridges [5]. Up to now, a large number of methodologies of optimal wired accelerometer placement have been developed for long-span bridge health monitoring based on different...
criterions, such as the effective independence (EI) method [6, 7], the QR decompose method [8, 9], the MinMAC algorithm [10], and so forth. A comprehensive survey of gradient-based local optimization methods for accelerometer placement can be found in Li et al. [11]. More recently, combinatorial optimization methods based on the biological and physical analogue have been extensively used for the optimization of optimal accelerometer placement problems due to their many advantages over the classical optimization techniques such as being a blind search method and being highly parallel. Among them, the most powerful heuristics are based on the genetic algorithms (GAs). Yao et al. [12] took GA as an alternative to the EFI method, and the determinant of the FIM is chosen as the objective function. Yi et al. [13, 14] improved some drawbacks of GAs and proposed a generalized genetic algorithm (GGA) for sensor placement of high-rise structural health monitoring. Moreover, the monkey algorithm (MA), which was firstly designed by Zhao and Tang [15] from the inspiration of mountain-climbing processes of monkeys, has been introduced in the field of optimal accelerometer placement by Yi et al. [16]. And then, the dual-structure coding method and asynchronous-climb process were incorporated in the MA, and the convergence speed is improved dramatically [17]. All of those methods mentioned before are fit for wired accelerometer, in which the distance between any two sensors is unconstrained.

Rapid advances in sensors, wireless communication, microelectromechanical systems (MEMS), and information technologies have significant impacts on SHM. Compared to conventional wired sensor, wireless sensor has many attractive features, including ease of installation, wireless communication, onboard computation, relatively low cost, and small size [18]. Several researchers have contributed to wireless sensors technology in monitoring bridge structures from sensor development and applications [19–27], providing important insight into the potential of wireless sensor networks (WSNs) technology for long-term monitoring. In real-world SHM of long-span bridges, linear network that the wireless sensors are deployed on the girder one by one along a straight line is adopted in common since the span is much larger than the height. In this type of WSN, multihop and single-line route are employed, and the nodes near the sink bear heavy transmission load. As a result, those nodes would deplete their energy quickly, leading to what is called an "energy hole" near the sink. A lot of energy of nodes far from the sink is wasted, which induces that the performance of the WSN is poor. The practical implements indicate that the limited energy of wireless sensor which is the
greatest obstacle that hinders dense network is distributed for long-term monitoring. Therefore, many contributions were conducted on eliminating “energy hole,” balancing energy consumption, and optimizing performance of WSNs. An analytical model for the “energy hole” problem in uniform node distribution WSNs was presented by Li and Mohapatra [28]. And then, Stojmenovic and Olariu [29] proved that the “energy hole” problem is unavoidable in WSNs if the nodes in the network are distributed uniformly and data are collected uniformly and discussed the possibility of the nonuniform node distribution strategies under different assumptions, respectively. Furthermore, Hossain et al. [32] provided an analytical method for placing a number of nodes in a linear array such that each node dissipates the same energy per data gathering cycle. It can be concluded from the presented achievements that nonuniform node distribution is a good configuration with respect to eliminating “energy hole.” However for WSNs of SHM, there are many special properties like high sampling frequency, continuous data flow and long-term monitoring, which induce that the existing methods cannot be used directly.

Being different from general WSNs that are used in habitat sensing, environmental monitoring, automated health care, and so forth, the sampling rate of WSN for long-span bridge health monitoring is more than 50 Hz in most occasions. So, the energy consumption for data sensing is significant and cannot be ignored. On the other hand, the nodes are distributed as a straight line along the bridge span. The data are transmitted by multihop and single-line route. This paper develops a nonuniform node configuration of WSN for long-span bridge health monitoring. A two-phase node arrangement method used for nonuniform node configuration is presented at first. Based on the introduced method, the WSN configurations under different test cases are carried out by a long-span suspension bridge, and the performances of those configurations are evaluated. Three cases with different sensor nodes and different monitoring requirements are executed, so that the performance of the WSN with nonuniform node configuration can be displayed extensively. For comparing the results of the two-phase node arrangement method, other WSN schemes with the same monitoring requirements are also provided.

2. Two-Phase Node Arrangement Method

Considering the cost of the WSN and the requirement of the bridge health monitoring, the reasonable strategy is that the WSN is organized by two types of nodes, sensor node and relay node, which is named as composite WSN. The sensor node and relay node have the same node platform. The relay node with low price does not instrument with sensor board. In this WSN, the sensor node is responsible for vibration monitoring and data retransmission, and the relay node is only responsible for retransmitting data. Therefore, the investment of the WSN deployment is reduced dramatically.

According to the characteristics of the composite WSN, two-phase node arrangement method can be adopted to implement the nonuniform node configuration. The first phase is sensor node arrangement to fulfill the requirement of the bridge health monitoring, and the second phase is relay node arrangement to balance the energy consumption of nodes in WSN and improve the performance of the WSN. In the phase of sensor node arrangement, there is no need to take the data transmission range into account for the existence of relay nodes. So, the improved general genetic algorithm (GGA), which is superior in biologics to the classical genetic algorithm (GA), is employed. The dual-structure coding system, in which the chromosomes of an individual are composed of append code and variable code, is used to initialize the population. The two-quarter selection, whose process is two-parent selection → crossover → a family of four → two-quarter selection → mutation → a family of four → two-quarter selection → next generation is introduced in the evolution. In the process of evolution, the gradual change and sudden change are combined to avoid local optimal solution. In general, the gradual change is adopted. When the best fitness value of the population keeps constant in several continuous generations, the evolutionary processing turns to sudden change. Until the best fitness value changes, the evolutionary processing turns back to the gradual change. The partially matched crossover (PMX) is applied in the crossover, while the swap mutation and inversion mutation are used in the gradual change and the sudden change, respectively. The modal strain energy (MSE) is taken as the fitness function in GGA. In the phase of relay node arrangement, the relay nodes are configured by the nonuniform node arrangement method based on the principle that the energy of all nodes in WSN is depleted almost simultaneously. Using the data acquisition efficiency (DAE) that is defined as data capacity per unit deployment cost, the closed-form solutions for the number and
3. Simulation Environment

The long-span suspension bridge, with main span of 1490 m, is used to demonstrate the effectiveness of the two-phase node arrangement method. The bridge is a single-span-double-joint steel box girder bridge. The width and height of the full-joint streamlined steel box girder are 36.3 and 3.0 m, respectively. 182 suspenders are used to transfer the load of girder to main cables, and the distance between two adjacent suspenders is 16.1 m. The two side spans are 470 m, and there is no suspender in the side span. The two towers with three-story frame structure are applied. The heights of the two towers are about 210 m. There are two tower columns with three prestressed concrete crossbeams (top, middle, and bottom crossbeams) in each tower. An updated three-dimensional finite element model is established in order to provide input data for the WSN arrangement. The main girder and main towers are simulated by spatial beam elements, and the main cables and suspenders are simulated by 3D linear elastic truss elements with three DOFs at each node. Then, the model shapes, and model frequencies can be obtained by model analysis. For simplicity, only vertical model shapes relating to main girder are accounted for here. The first six vertical model shapes are plotted in Figure 1, and the first eight vertical model frequencies are listed in Table 1. The 1st vertical model frequency is only 0.0879 Hz, no more than 0.1 Hz, which reveals the super low stiffness of this long-span suspension bridge.

The parameters of node are listed in Table 2 [33]. In the table, $E_0$ represents the initial energy of node, $d_{max}$ represents the maximum radio range of node, $l$ represents data quantity per collecting cycle, $d_0$ represents a node specific critical distance, $\alpha$, $\gamma$, and $\eta$ represent node specific energy consumption coefficients in the transmitter circuitry, receiver circuitry, and sensor circuitry, respectively; $\beta_1$ and $\beta_2$ represent the energy required to transmit per bit over a per unit distance in different cases, and $a$ and $b$ represent the cost per sensor node and per relay node, respectively. The parameter about sensing data is excluded by relay node.

Three cases, which are four sensor nodes placed in the same girder side, ten sensor nodes placed in the same girder side, and eight sensor nodes placed averagely in two girder sides, are considered here.

4. Results Analysis

4.1. Case I. In this case, a total number of four sensors are used for vertical vibration monitoring. The two-phase node arrangement is carried out. In the first phase, the locations of sensor nodes are optimized by improved GGA; in the second phase, the relay nodes are configured by nonuniform node arrangement method.

It is well known that the path of searching is selected randomly in random search algorithm, so the different results are obtained by several times of calculation. The better choice is selecting the best one from those results. For the GGA, there are a number of parameters that are problem specific and need to be explored and tuned so that the best algorithm performance is achieved. The population size of 300 is selected. The GGA processes have been run for 10 times with different stochastic initial populations, and the best one is adopted. The fitness convergence curves are shown in Figure 2. It can be seen that only 54 generations are needed to reach the optimal value. The maximum fitness values tend to a constant quickly, and the average values and the minimum
The symbol \( R_i \) denotes the relay node belonging to the interval of sensor nodes \( S_i \) and \( S_{i-1} \). The distance between adjacent relay nodes \( R_{i,j} \) and \( R_{i,j-1} \). The distance between \( S_i \) and \( R_{i,j} \) is denoted as \( d_{i,j} \). The values of \( m_i \), \( d_{i,j} \), and \( d_{i,j-1} \) are calculated through the nonuniform node arrangement method. Besides scheme I, other two schemes with the same number of relay nodes are also employed for comparison. Scheme II is a uniform configuration, and the relay nodes are placed uniformly, which is very popular in vibration monitoring of long-span bridges, and can be executed easily. The sketch of this scheme is not displayed for its simplicity. In this scheme, the number of relay nodes is assigned to sensor nodes interval proportional to the distance between two adjacent sensor nodes. Because the computed number of relay nodes is integrated, the distances of adjacent relay nodes are not equal accurately. Scheme III is an independent sensor node configuration, and the sensor node is only responsible for sensing data and transmitting it, as shown in Figure 4.

In this scheme, the energy of sensor nodes is saved. The number of relay nodes is assigned to sensor nodes interval proportional to the values of which the distance between two adjacent sensor nodes multiplies with quantity of transmitted data. The detailed node configurations of the three schemes are listed in Table 4. In the table, DAE represents the data acquisition efficiency. In scheme I, the nearer the relay nodes are close to the sink, the shorter the distance of two adjacent relay nodes is. However, it is not proportional to distance from the relay node to the sink. Both the sensor nodes and the relay nodes are arranged nonuniformly. In scheme II, the distances of node intervals are almost equal. In scheme III, although the distances of node intervals are nonuniform, the WSN is not optimized completely. When comparing network lifetime and DAE in Table 3, it can be seen that scheme I has the longest network lifetime and highest DAE, which indicates the highest performance of this scheme. The network lifetime of scheme II is no more than half of that of scheme I. This scheme has the lowest DAE, although it is the most common one in practice. In scheme III, the sensor nodes are protected perfectly, but their potential is not stimulated. So, the DAE of this scheme is lower than that of scheme I.

![Figure 4: Independent sensor node configuration (unit: m).](image-url)
Table 4: Node arrangements of different schemes.

| Scheme   | $d_{4,S}$ | $d_{4,R}$ | $d_{3,S}$ | $d_{3,R}$ | $d_{2,S}$ | $d_{2,R}$ | $d_{1,S}$ | $d_{1,R}$ | Total node | Network lifetime (Unite: s) | DAE   |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-------------|--------------------------|-------|
| Scheme I | 37.56     | 37.22     | 31.25     | 31.00     | 26.86     | 26.56     | 25.06     | 24.21     | 34          | $3.81 \times 10^4$         | 3.26  |
| Scheme II| 33.86     | 33.86     | 31.04     | 31.04     | 31.04     | 33.86     | 33.86     | 34         | $1.49 \times 10^5$         | 1.28  |
| Scheme III | 20.69   | 41.39     | 31.04     | 31.04     | 31.04     | 28.65     | 28.65     | 34         | $2.57 \times 10^4$         | 2.20  |

Figure 5: Residual energy of nodes in different schemes.

Figure 6: Evolution progress of the GGA with ten sensors.

Figure 7: Residual energy of nodes in scheme I.

Figure 8: Residual energy of nodes in scheme II.

Figure 9: Residual energy of nodes in scheme III.

balancing energy consumption, the maximum performance can be obtained in scheme I.

4.2 Case II. In this case, 10 sensor nodes are adopted. Similarly, the sensor nodes are firstly placed by improved GGA. And then, the relay nodes are distributed by nonuniform node arrangement method. The population size of 500 is used this time. The process of convergence is shown in Figure 6. The excellent ability of global optimal solution searching of improved GGA is demonstrated also. The maximum fitness value converges to the best quickly. Three schemes like case I are employed also. The sampling frequency of different
sensor is specified by different value. The performance of the three WSN schemes is listed in Table 5. The highest value of network lifetime and DAE is acquired in nonuniform configuration. The network lifetime and DAE of other two schemes are much less than that of scheme I. The residual energy of nodes in scheme I, II and III, is given in Figures 7, 8, and 9, respectively. Like case I, the node configuration arranged by the two-phase node arrangement method has the lowest residual energy. The maximum residual energy is only 1.81 J. Comparing with that in Figure 5(a), the value of residual energy shows a few changes. The robustness of the proposed method is validated. In scheme II, the maximum residual energy is 3.74 J, more than 90% of the initial energy of the node. Big “energy hole” is formed in this network. When compared with scheme II in case I, with the number of nodes increasing, more energy is left. It can be deduced that there may be no data transmitted to sink when the scale of this type of WSN scheme is big enough. In scheme III, the residual energy is almost 30 J, which is similar in case I. When 10 sensor nodes are used, the best performance is also shown in scheme I.

4.3. Case III. Because of the low stiffness, the torsional vibration of the long-span bridges under skew wind or other nonuniform excitation cannot be neglected on some occasions. To monitor the torsional vibration, accelerometers should be placed on the two sides of the girder, assuming there are four sensor nodes on each side. Two schemes are discussed in this case. In scheme I, the data on each side are transmitted independently and gathered to sink at last, as displayed in Figure 10. So, there are two independent linear arrays in the WSN. And in scheme II, one linear array placed in the isolation strip that is only organized by relay nodes is used for retransmitting data, as shown in Figure 11. The sensor nodes are only responsible for collecting data and transmitting it to the nearest relay node.

After calculating, the network lifetime and DAE of scheme I are $3.81 \times 10^4$ and $3.26 \times 10^4$, respectively, and those of scheme II are $1.76 \times 10^4$ and $2.50 \times 10^4$, respectively. Although the total number of relay nodes in scheme I is much more than that in scheme II, the network lifetime is longer, and the DAE is higher. The higher performance

| Scheme | Total node | Network lifetime (unit: s) | DAE (unit: J) |
|--------|------------|---------------------------|--------------|
| Scheme I | 70 | $4.52 \times 10^4$ | $4.67 \times 10^3$ |
| Scheme II | 70 | $1.89 \times 10^4$ | $1.95 \times 10^4$ |
| Scheme III | 70 | $3.21 \times 10^4$ | $3.32 \times 10^4$ |
of nonuniform node configuration arranged by proposed method is displayed obviously.

5. Conclusions

WSNs, which are identified as one of the most important technologies of the XXI century, have been widely used in SHM of long-span bridges. The limited energy of sensor node makes the performance of WSNs sensitive to energy consumption of every node in network. For WSN of long-span bridge health monitoring, the performance is critical since the test with long period and high sampling rate is required. Through balancing energy consumption, avoiding “energy hole,” and increasing data capacity, the performance of WSNs can be improved. The performance of nonuniform node configuration that is deployed by two-phase node arrangement method is demonstrated by three different cases. In every case, the scheme configured by the proposed method is compared with other scheme. In the uniform configuration, the “energy hole” cannot be avoided. The bigger the network is, the more energy is wasted. The performance of the uniform WSN is so poor that it is not fit for linear network. In the independent sensor node configuration, the sensor nodes are removed from the route of data retransmission. So, the potential of sensor nodes is not utilized adequately. The performance of this type of configuration is a little worse than that of the nonuniform node configuration. In the nonuniform node configuration deployed by the two-phase node arrangement method, the energy of nodes is consumed almost synchronously. The longest network lifetime and the highest DAE are obtained in this configuration, and the most outstanding performance is shown. At the same time, the performance is stable on different test occasions. In the simulation, there are no special requirements presented; so the proposed two-phase node arrangement method can be used for WSN configuration of real-word long-span bridge health monitoring with the main properties of high sampling frequency, continuous data flow, and long-term monitoring extensively.

It should be noted that the results in this paper are deduced based on the assumed theoretical models. The real environments of WSN are more complex, and many others factors affect the performance of WSNs. More factors influencing the performance of WSNs such as quality of service, energy efficiency route, and network topology should be further performed in the future to the generalization of the model developed in this paper.

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