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Analysis of bridge construction monitoring based on bim spatio temporal similarity attributes perception

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Abstract. In order to solve the problem that bridge monitoring public network signal in remote areas can not meet the transmission requirements and difficulties in stationing and wiring for traditional bridge monitoring, the application of building information model (BIM) to bridge engineering can significantly improve the efficiency of design and construction of bridges. BIM, based on engineering data, integrates data model of relevant information concerning bridge engineering projects, with the function of monitoring the whole project cycle and putting forward optimization scheme of design and construction of bridge based on BIM through analyzing the characteristics of bridge engineering and its potential risks. Firstly, take advantage that wireless sensor network is convenient to layout network, introduce wireless sensor network to remote monitoring of bridge, and meanwhile solve the problem of blind area in bridge monitoring signal communication in remote mountainous areas through domestic independent Beidou satellite communication technology. Experiments show that the monitoring system based on wireless sensor network can meet the application requirements of bridge remote monitoring, especially in remote mountainous areas, multi-node wireless sensor network can effectively improve the accuracy of monitoring and reduce the energy consumption of the network monitoring through the weighted optimal information fusion.

Key words. WSN, Bridge remote monitoring, BIM, Satellite communication, Signal blind area, Node deployment.

1. Introduction

With the development of society, the bridge plays an irreplaceable role in the transportation system as an important hub. Because of the long-term effects of

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sudden geological disasters, increasingly complex natural climate, increased traffic, material aging, corrosion effect, fatigue effect and other unfavorable factors on bridges facilities[1, 2], bridge structures would inevitably produce natural aging, damage accumulation, deformation and other damages and fatigues and additional natural disasters as floods, earthquakes, etc, which results in frequent bridge safety accidents, making people pay more and more attention to bridge safety and durability.

Wired sensors are adopted in most existing bridge monitoring systems, monitoring network constructed by wired sensors features in large amount of wiring, complex wiring, high maintenance costs and wired mode is difficult to achieve effective communication in bridge monitoring in remote mountainous areas. With the rapid development of embedded computing technology, communication technology and sensor technology and MEMS technology becoming more and more mature and perfect, micro sensors with capability of sensing, computing and communication are generated. Numerous micro sensor nodes are connected wireless to cooperate with each other and interact with the physical world and work together on a specific application task to constitute wireless sensor network[3, 4]. Wireless sensor network features wide distribution, low cost, good fault tolerance, remote monitoring, easy for diagnosis and maintenance, which was widely applied in military defense, environmental monitoring, intelligent traffic management, health and other fields[5, 6], and also be listed as one of the 21 most influential technologies and one of the top 10 technologies to change the world in 21st Century.

2. Overall design of bridge monitoring system

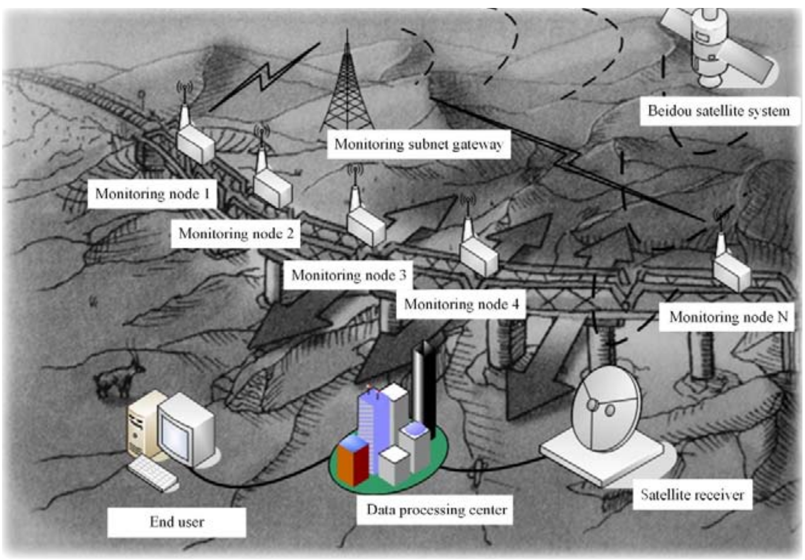

Fig. 1. The structure of landslide remote monitoring sub network

For application environment of bridge remote monitoring, especially bridge remote monitoring in mountainous areas, combine current development and application status of wireless sensor network technology to design a bridge wireless sensor network based on wireless sensor network and Beidou satellite system, which is mainly composed of monitoring nodes, sink nodes, Subnet gateways and data processing center, The network structure is shown in Fig. 1.

In the whole monitoring system, the wireless sensor network, which is composed of the monitoring node and the sink node, is the core part of the whole network and the key research object. The monitoring nodes are located in key monitoring areas such as bridge deck or bridge pier to realize information collection of the bridge state. The collected information in bridge monitoring includes bridge load environmental monitoring (vehicle load, temperature, wind speed and direction, etc.), overall performance monitoring of bridge structures (bridge vibration characteristics, structural displacement monitoring, etc.) and the key sections of bridge stress (strain) monitoring, etc. The convergence nodes mainly achieve that the information of the monitoring area is processed to a higher level network to complete the convergence and forwarding function of the monitoring information. Subnet gateway nodes can be understood as a more powerful aggregation node, which usually has a variety of communication functions to solve the long distance wireless communication of monitoring system, subnet gateway nodes are mainly responsible for converting different communication protocols, communicating with upper network, forwarding user instruction down to manage layer monitoring network, and transmitting up the monitoring data collected by the wireless sensor network nodes, etc. The data processing center mainly achieves functions of integral safety and reliability monitoring of bridges, evaluation of life, perform data synthesis of monitoring information collected by monitoring system and long-term and short-term required structure and status information of bridges to complete data analysis and interpretation, assessment and decision of structure and condition, etc.

3. Mesh topology structure of wireless sensor of bridge remote monitoring

In wireless sensor network system of bridge remote monitoring, design of wireless sensor network is different from other engineering applications, nodes used for monitoring the state of bridge are layout with zonal distribution in the bridge on the whole, which is different from mesh topology structure of traditional wireless sensor network with a large number of random nodes and ad hoc network, mesh topology of wireless sensor used for bridge remote monitoring is a typical zonal mesh topology structure, as shown in Fig. 2.

Zonal mesh topology structure is a typical wireless sensor mesh topology structure, which is mainly featured by nodes distributed in narrow areas, and traffic monitoring and bridge monitoring are typical applications of zonal mesh topology structure [13]. In remote monitoring network of bridge, the zonal mesh topology is in a tree-shaped chain structure, borrow the concept of hierarchical network [7], the network is divided into two layers, among which the underlying layer is the sensor

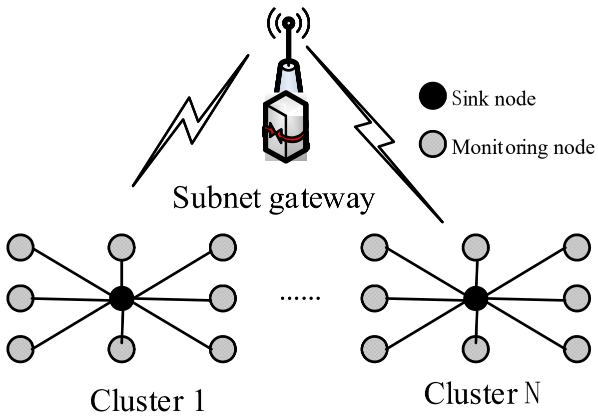

Fig. 2. The structure of mesh topology

nodes collecting environmental parameters and the top layer is network sink node, which gathers information in the region and transfer it to a higher level network after data fusion. Because of the particularity of zonal network, divide underlying network into multiple clusters according to geographical location, among which monitoring nodes in each cluster collect monitoring information of the monitored area, and then sent to the sink node of the cluster, which is distributed processing center, each cluster member transmits data to the sink node, in which data processing and fusion is completed, and then other nodes forward to monitoring subnet gateway by multi hop forwarding or direct single hop. As a result, this kind of cluster-based network has natural distributed processing capability.

4. Hardware design

The core of the whole bridge remote monitoring system is composed of monitoring nodes and sink nodes. The monitoring node mainly realizes the collection and transmission of the bridge monitoring information, while the sink node is mainly used for the preliminary processing and relay forwarding of the monitoring signal.

In different application environment, sensor nodes are slightly different in composition, but include the following basic modules [8]: sensor module (sensitive components, signal conditioning and analog conversion, etc), processor module (CPU, Storage, etc), wireless communication module and power supply module (including power supply and related power management). Monitoring node uses CC2530 of TI as core components, hardware architecture of monitoring node part is as shown in Fig.3. C2430 integrated enhanced 8051 MCU, flash storage, SRAM and RF transceiver, supporting 2.4GHz IEEE 802.15.4/ZigBee protocol; current consumption of CC2530 is of mA level at work, while only 0.9μA in resting mode, the characteristics of low energy consumption is very suitable for bridge remote monitoring in work environment of remote mountainous areas in which replacing the power supply is inconvenient [9].

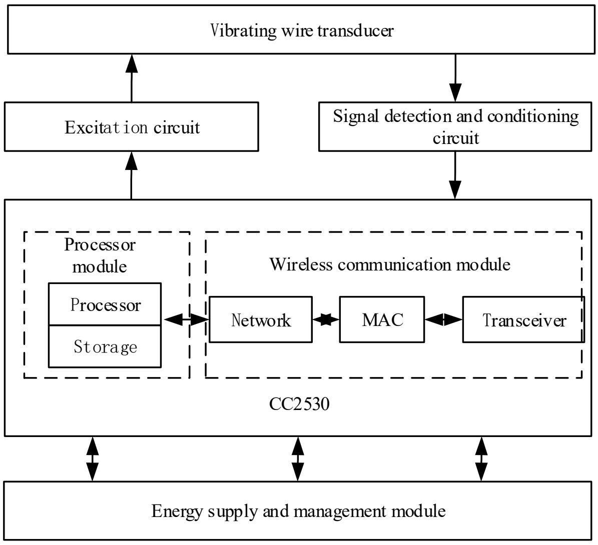

Fig. 3. Hardware architecture of monitoring node

Bridge monitoring information includes bridge load environment monitoring (vehicle load, temperature, wind speed and direction, etc), the whole bridge structure performance monitoring (vibration characteristics and structural displacement monitoring of bridge) and the key sections of bridge stress (strain) monitoring, The corresponding monitoring information acquisition requires specific sensors. In this paper, the vibration characteristics of the bridge are monitored by vibrating wire transducer [20], which needs external excitation, including current and electromagnetic excitation. The current excitation mode is adopted in the system, the CC2530 outputs a certain frequency sweep signal by programming, which is converted to the working current signal excitation required by vibrating wire transducer by operational amplifier. Vibrating wire transducer outputs frequency signal, which is weak and mixed with other noise signals. Therefore, signal detection and conditioning circuit is required to filter out the signal noise and amplify the useful frequency signal to CC2530 processor for processing. The sink node can be composed of the same node as the monitoring node, or the monitoring node removed part functions of transducers to only complete signal forwarding function.

In bridge remote monitoring, because many bridges are located in remote mountainous areas, in which public network signal such as GSM can not be guaranteed and communication distance based on the Zigbee wireless sensor network is limited, making it unable to realize the long distance wireless communication [19]. With the development of Beidou communication satellite system with China's independent intellectual property rights, Beidou communication satellite technology is more and more widely applied in military and civilian areas, and the technology is more mature with lower cost. Therefore, the Beidou satellite communication technology is introduced in the system to solve the problem of long distance communication and communication blind zone. The hardware architecture of the monitoring subnet gateway (Fig. 4) mainly includes the MCU, the ZigBee communication module, Beidou satellite communication device, etc. The MCU is mainly used for automatic control and management of various wireless and wired networks. ZigBee communication module and sensor node wireless communication module also uses CC2530. Beidou satellite communication device selects the BD-1 universal user. Beidou satellite system can provide two-way short message communication and precise time service at any time and any place in the service area. BD-1 universal user can achieve the data forwarding function through the BD-1 satellite to achieve the transmission and real-time monitoring of monitoring data.

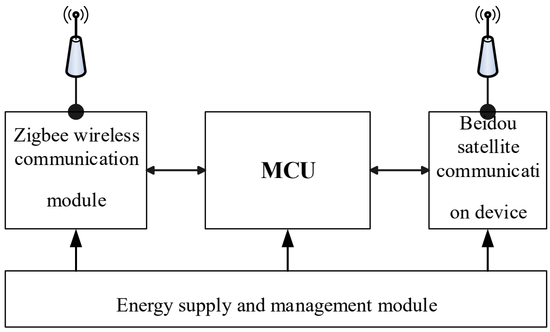

Fig. 4. Hardware architecture of monitoring sub network gateway

5. Monitoring information integration

Data collected by the monitoring nodes is in huge size, and the information collected by the nodes in the same area is very redundant. Therefore, it can save energy effectively by improving the accuracy of monitoring data and reducing the amount of data transmission through local calculation and integration. In this system, each monitoring node in the cluster sends the monitoring data to the sink node which is for data integration by using optimal weighting algorithm. The integration results are the results of the whole cluster for the purpose of decreasing the amount of data transmission in the network to reduce the power consumption of communication and prolong the network lifetime. The core idea of the optimal weighting algorithm is to find the optimal weighting factor corresponding to each node according to the measured value of each node in the self-adaptive manner under the premise of the minimum and optimal mean square error of weighted estimation to optimize [10–12] the measured data after integration of weighting factor.

As shown in the information integration modes in Fig.3, a cluster consists of Nnodes and the target parameters are tested by all the nodes in cluster from the different positions. Output equation of the ith node is $Yi{=}X{+}Vi$ (Yi is the output value of node measurement, X as the estimated true value and Vi as the measured noise), which satisfies $E\left[V_i\right] = 0, D\left[V_i\right] = \sigma_i^2$. It can be assumed that measured noises of nodes are uncorrelated for the random noise, namely $E[ViVj] = 0$, $(i \neq j)$. It is supposed that weighting factors of all the nodes are $\alpha_1, \alpha_2, \ldots, \alpha_N$respectively, and then the weighted estimated value $\hat{X}$ is:

$$\hat{X} = \sum_{i=1}^{N} \alpha_i Y_i \,. \tag{1}$$

According to the unbiased estimation theory, it is necessary to meet the condition $E[\hat{X}] = X$ for ensuring unbiased estimation, namely

$$\begin{aligned} E[\hat{X}] &= E\left[\sum_{i=1}^{N} \alpha_i Y_i\right] = E\left[\sum_{i=1}^{N} \alpha_i (X + V_i)\right] \\ &= E\left[\sum_{i=1}^{N} \alpha_i X\right] + E\left[\sum_{i=1}^{N} \alpha_i V_i\right] = X \sum_{i=1}^{N} \alpha_i = X \,. \end{aligned} \tag{2}$$

Obviously, $\hat{X}$ is the unbiased estimation of X when the condition $\sum\limits_{i=1}^{N} \alpha_i = 1$ is satisfied.

At the same time, it is necessary to minimize the mean square error of weighted estimation for the optimal weight. It is supposed that mean square error of weighted estimation is σ_2, then

$$\begin{aligned} \sigma^2 &= E\left[\left(X - \hat{X}\right)^2\right] = E\left[\left(X - \sum_{i=1}^{N} \alpha_i Y_i\right)^2\right] \\ &= E\left[\left(X - \sum_{i=1}^{N} \alpha_i \left(X + V_i\right)\right)^2\right] \\ &= E\left[(X - X \sum_{i=1}^{N} \alpha_i - \sum_{i=1}^{N} \alpha_i V_i)\right] \\ &= E\left[\left(\sum_{i=1}^{N} \alpha_i V_i\right)^2\right] = \sum_{i=1}^{N} \alpha_i^2 \sigma_i^2 \,. \end{aligned} \tag{3}$$

It can be known from formula (3) that σ_2, the mean square error of weighted estimation, is the binary quadratic function of α_i, the each weighting factors. Therefore, there must be the minimum σ_2. The following auxiliary function is constructed with the method of Lagrange conditional extremum according to the extremum theory of multivariate function:

$$f(\alpha_1, \alpha_2, \ldots, \alpha_N, \lambda) = \sum_{i=1}^{N} \alpha_i^2 \sigma_i^2 - \lambda \left(\sum_{i=1}^{N} \alpha_i - 1\right) \,. \tag{4}$$

The weighting factor corresponding to the minimum mean square error of weighted estimation is obtained as follows based on this equation:

$$\alpha_K^* = \frac{1}{\sigma_K^2 \sum\limits_{i=1}^{N} \frac{1}{\sigma_i^2}}, K = 1, 2, \ldots, N\,. \tag{5}$$

Then the minimum mean square error of weighted estimation under the optimal weighting factor is:

$$\sigma_{\min}^2 = \frac{1}{\sum\limits_{i=1}^{N} \frac{1}{\sigma_i^2}}, i = 1, 2, \ldots, N\,. \tag{6}$$

It can be known from formula (5) that the smaller the noise variance is, the larger the weight of node is and the higher the proportion of measured value of node in the weighted estimate is so that the weighted measured data is closer to the actual true value.

In a word, we can see that output of sink node is:

$$C' = \sum_{k=1}^{N} \left(\frac{1}{\sigma_K^2 \sum\limits_{i=1}^{N} \frac{1}{\sigma_i^2}} * Y_K \right). \tag{7}$$

6. Experimental analysis

The wireless sensor network of monitoring system is verified in experiment only based on the existing experimental platform of wireless sensor network due to the lack of application equipment of Beidou satellite communication system. It is simulated and monitored on a bridge model where 12 wireless sensor network nodes are distributed in the band to constitute 3 monitoring subnets. 3 different parts of the bridge model are monitored separately. Monitoring information is collected by monitoring nodes arranged in the monitoring area with the vibrating string sensor to be sent to sink node for integration, processing and output, and the test results are shown in Table 1.

It can be seen from experimental results that all the monitoring nodes in monitoring subnet 1 and 3 work normally except a monitoring node in monitoring subnet 2 failed to acquire monitoring data normally due to fault. Monitoring information collected by each monitoring node is different since affected by the noise and system error, but the difference between integrated results output from sink node is small than that collected by single monitoring node in each monitoring subnet; at the same time, the whole monitoring subnet will not be affected by individual abnormal monitoring nodes, so the system robustness is improved. The amount of data needed to be transmitted in the whole monitoring subnet is greatly reduced after integration in sink node, which can effectively reduce the energy consumption of the whole network and prolong the service life of the wireless sensor network.

Table 1. Monitoring results of wireless sensor networks

Monitoring subnet	Monitoring node	Integration output of sink node (kHz)	ntegration output (kHz)
1	1	20.28	20.15
	2	20.80	
	3	19.34	
2	1	30.19	30.01
	2	0	
	3	29.14	
3	1	40.24	40.16
	2	38.45	
	3	39.23	

7. Conclusion

In this paper, the wireless sensor network and Beidou satellite communication technology are introduced to application of bridge remote monitoring, and the application of BIM technology in bridge engineering can effectively manage bridge construction, greatly reduce the safety risks in bridge construction and better realize the design intent. Establishment of bridge remote monitoring model and integration of monitoring information with optimal weighted algorithm have improved monitoring accuracy and robust system, effectively reduced the amount of data transmission and saved the energy consumption of network. Bridge monitoring is complex systematic engineering, including information analysis, prediction, evaluation and other systematic sciences. It is the next focus to research how to improve the monitoring methods and analysis and evaluation technology of monitoring information to effectively monitor the operation state of bridge, accurately predict and evaluate the safety risks for promoting life and property safety of people and national economic development.

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