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Development of a Wireless Cable Tension Monitoring System using Smart Sensors

Sung-Han Sim[1], Jian Li[2], Hongki Jo[3], Jong-Woong Park[4], and Billie F. Spencer, Jr.[5]

[1] School of Urban and Environmental Engineering, UNIST, Ulsan 689-798, Korea
[2], [3], [5] Dept. of Civil and Environmental Engineering, Univ. of Illinois, IL 61801, USA
[4] Department of Civil Engineering, KAIST, Daejeon 305-701, Korea
[1] ssim@unist.ac.kr

ABSTRACT

Central data acquisition systems associated with wired sensors have been conventionally used for infrastructure monitoring, which is quite challenging due to difficulties in cabling, long setup time, and high equipment and maintenance costs. To overcome such difficulties found in the traditional wired sensor systems, smart sensors have developed as a promising alternative. Recent advances in sensor technology have realized low-cost, smart sensors with on-board computation and wireless communication capabilities, making deployment of a dense array of sensors on large civil structures both feasible and economical. However, the centralized data collection typically used in the wired sensor system is no longer tractable in the network of smart sensors that uses wireless communication due to the limited bandwidth. Thus, the wireless smart sensor network (WSSN) requires appropriate in-network data processing schemes for efficient operation with minimized data transmission; to date such algorithms are limited. This research develops a new decentralized approach for monitoring cable tension forces of cable-stayed bridges. The performance of the decentralized approach and its software implementation are validated through full-scale application at the Jindo Bridge, a 484m cable-stayed bridge in South Korea. Temperature dependencies of the cable tension are identified. This research provides a strong foundation for long-term monitoring employing a dense array of smart sensors.

[1] Assistant Professor
[2] Graduate Research Assistant
[3] Graduate Research Assistant
[4] Graduate Research Assistant
[5] Nathan M. and Anne M. Newmark Endowed Chair in Civil Engineering

1. INTRODUCTION

In the civil engineering field, Structural Health Monitoring (SHM) has become a prominent tool to address problems associated with deteriorating civil infrastructure. Data acquisition in traditional SHM systems is based on wired sensors connected to a centralized data collection repository. All sensor data is aggregated at this central repository, where all data processing takes place to extract structural features and information. This centralized data acquisition and processing approach in the wired sensor network is common practice in traditional SHM systems; however, high cost and installation difficulties (Lynch et al. 2003) have prevented SHM from wider adoption in large-scale civil structures. For instance, imagine a SHM system of the Golden Gate Bridge; miles of cables would be required to connect the central base station to a dense array of sensor nodes distributed along the deck, towers, and cables; installation would be both costly and time-consuming, and maintenance would be challenging.

Wireless smart sensor networks provide a promising alternative to the traditional SHM approach. Smart sensors commonly refer to devices that are small, inexpensive, capable of wireless communication, and have on-board processing capabilities (Spencer et al. 2004). In the last decades, many academic and commercial smart sensors have been developed. Significant efforts have been devoted to various issues in Wireless Smart Sensor Networks (WSSNs), including data acquisition, processing, and damage detection. The majority of smart sensor research has focused on emulation of traditional wired sensor networks employing centralized data acquisition and processing. Such approaches have proven to be intractable because transferring all sensor data saturate the limited bandwidth found in wireless communication and thus causes network congestion. Indeed, decentralized data acquisition and processing schemes are considered to be essential to ensure the scalability of WSSNs required to enable a dense array of sensors deployed on full-scale civil structures. Considering that structural damage is a local phenomenon, densely deployed sensor networks are expected to enhance the damage detection capability of SHM systems.

This study presents a decentralized approach for monitoring cable tension of cable-stayed bridges. Software development of cable tension for smart sensors is described in detail. A smart sensor application implementing cable tension estimation is validated through full-scale experiments at the Jindo Bridge, a 484m cable-stayed bridge located in South Korea.

2. DECENTRALIZED CABLE TENSION MONITORING

A cable tension estimation method based on the closed form relationship between natural frequencies and a tension force is considered as this method is suitable for an automated system. For completeness, the estimation method used in this study is described here. Assuming the tension force T is constant over the entire cable, the equation of motion of the inclined cable shown in Figure 1 can be written as (Shimada 1994):

$$\frac{w}{g}\frac{\partial^2 z}{\partial t^2} + EI\frac{\partial^4 z}{\partial x^4} - T\frac{\partial^2 z}{\partial x^2} = 0 \tag{1}$$

where z is the deflection in the y-direction, w is the weight density per length, EI is the flexural rigidity, and g is the gravity. Assuming pinned boundary conditions, the solution is:

$$\left(\frac{f_n}{n}\right)^2 = \frac{Tg}{4wL^2} + \frac{EI\pi^2 g}{4wL^4} n^2 \tag{2}$$

where L is the length of the cable, f_n is the natural frequency, and n is the order of the natural mode. Linear regression with $(f_n/n)^2$ and n^2 leads to estimation of the tension force T.

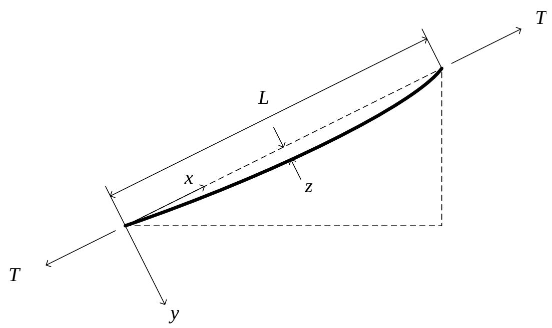

Figure 1. Inclined cable.

Despite sag and extensibility are neglected, this simple approach can be a practical solution for an automated cable tension estimation system. In addition, as this estimation method involves linear regression of many natural modes, difficulties in distinguishing the cable dynamics and the cable-deck interaction can be easily evaded by discarding low frequency modes that can be in the range of the cable-deck interaction. Implementation of this estimation method on WSSN is described in the following section.

3. IMPLEMENTATION

The estimation method described previously only uses information corresponding to each cable (e.g., sectional and material properties and natural frequencies); thus, information sharing between sensor nodes attached on different cables is unnecessary. Thus, the independent processing is suitable for implementation of the cable tension estimation method on WSSN.

CableTensionEstimation is a WSSN application that calculates cable tensions based-on the previously described vibration-based method. *CableTensionEstimation* first performs sensing and estimate the power spectrum that can provide natural frequencies of each cable using an automated peak-picking method; cable tension can be obtained using these natural frequencies.

To accurately find natural frequencies of cables, a peak-picking procedure is enhanced by employing curve-fitting of peaks in power spectra to those of single degree-of-freedom (SDOF) system. The enhanced peak-picking is implemented in

CableTensionEstimation: a peak is searched in a small frequency range around an approximate natural frequency initially provided to *CableTensionEstimation* and subsequently the curve-fitting to a peak of the SDOF system. Two assumptions are reasonably made to justify the enhanced peak-picking method: (1) the natural frequencies of the cable are well separated and (2) the changes over time are small compared to difference between two consecutive natural frequencies.

4. VALIDATION IN THE JINDO BRIDGE

The Jindo Bridges pictured in Figure 2 are twin cable-stayed bridges constructed in 1984 (the 1st Jindo Bridge) and 2005 (the 2nd Jindo Bridge) to connect Jindo Island and the town of Haenam, located at the southeastern part of the Korean Peninsula. The 2nd Jindo Bridge, on the left in Figure 2, is the test bed in the deployment. 'Jindo Bridge' indicates the 2nd Jindo Bridge in the rest of this document. The Jindo Bridge features three continuous spans (344 m mid-span, 70 m for each side-span) and a total of 60 steel cables that support the bridge deck. The pylons are located on land due to the high-speed tidal currents; thus, bridge scour is not a concern. Instead, wind- and traffic-induced vibrations are a potential threat to structural health for this lightly damped structure.

Figure 2. Jindo Bridges (1st: right, 2nd: left).

The WSSN deployed on the Jindo Bridge consists of 113 Imote2 (see Figure 3) sensor nodes. The network includes 48 nodes on cables, 56 nodes under the bridge deck, 6 nodes on the pylons, 3 anemometers, and 2 base stations. To achieve long-term monitoring, all sensor nodes are equipped with solar panels and rechargeable batteries, as wells as environmentally hardened enclosures. As this study focuses on monitoring cable tension, only sensor nodes on cables are considered hereafter.

The tension forces of the cables are estimated on the sensor nodes shown in Figure 4. For this paper, the sensor nodes located on the south-east side of the Jindo Bridge are utilized in the cable tension monitoring. *AutoMonitor* at the gateway node, an application that controls the whole network, runs *CableTensionEstimation* on a regular basis with the predefined time interval (24 hours), saving the retrieved cable tension values in the base station.

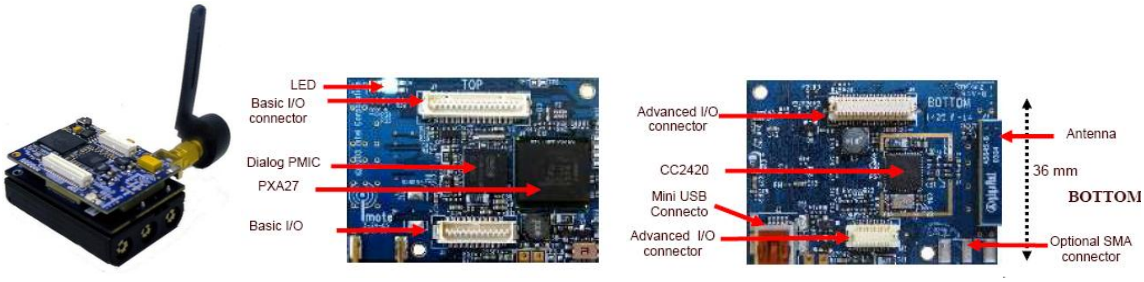

Figure 3. MEMSIC's Imote2 sensor platform.

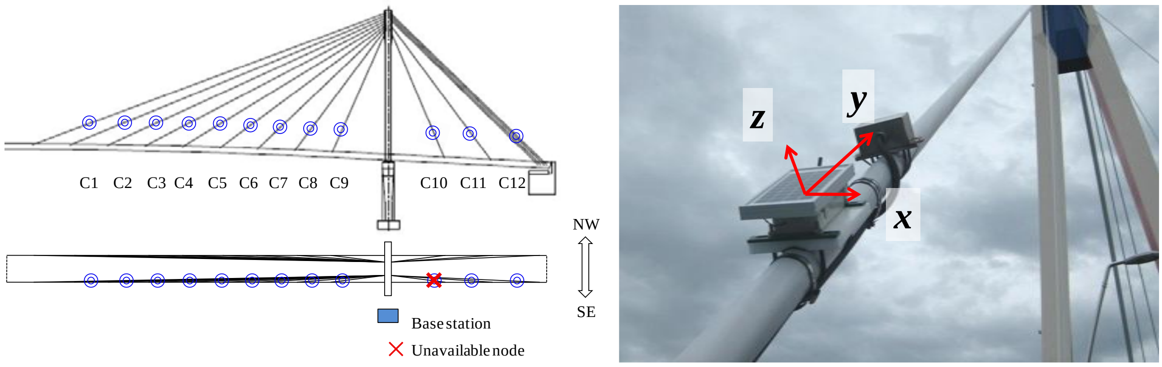

Figure 4. Cable nodes at the Cable-Haenam network and local axes.

In the initialization step prior to the autonomous operation of *CableTensionEstimation*, reference natural frequencies should be determined for the enhanced peak-picking method to use these frequencies in search of true natural frequencies at the time of sensing. The reference frequencies are subsequently stored in the network and used when *CableTensionEstimation* is running.

To obtain these reference frequencies, the power spectrum of measured accelerations are used. Local axes are defined as shown in Figure 4. Because using both x- and z-axis is redundant for identification of natural frequencies, only the z-accelerations are used for *CableTensionEstimation*. Natural frequencies for each cable node, as well as properties of cables stored in the gateway node, are disseminated to each sensor node to use for estimation of cable tension.

Cable tensions are tracked with temperature using *CableTensionEstimation* in conjunction with *AutoMonitor* as shown in Figure 5. The monitoring had been conducted from June 1, 2012 to July 5, 2012, measuring three times a day. While some of them are not obtained due to poor communication, varying cable tensions are in most cases successfully collected, showing the feasibility of the wireless monitoring system. The coefficient of variation (standard deviation divided by mean) is mostly less than 0.01 while C9 and C12 have larger values than 0.01. These variations in each cable are considered to be reasonably small, implying that no particular event has been occurred during the monitoring.

Cable tensions are observed to be weakly correlated to measured temperature. Note that the cable tension and temperature between 10^{th} and 20^{th} CTE runs of Cable 4 shows a relatively strong dependency.

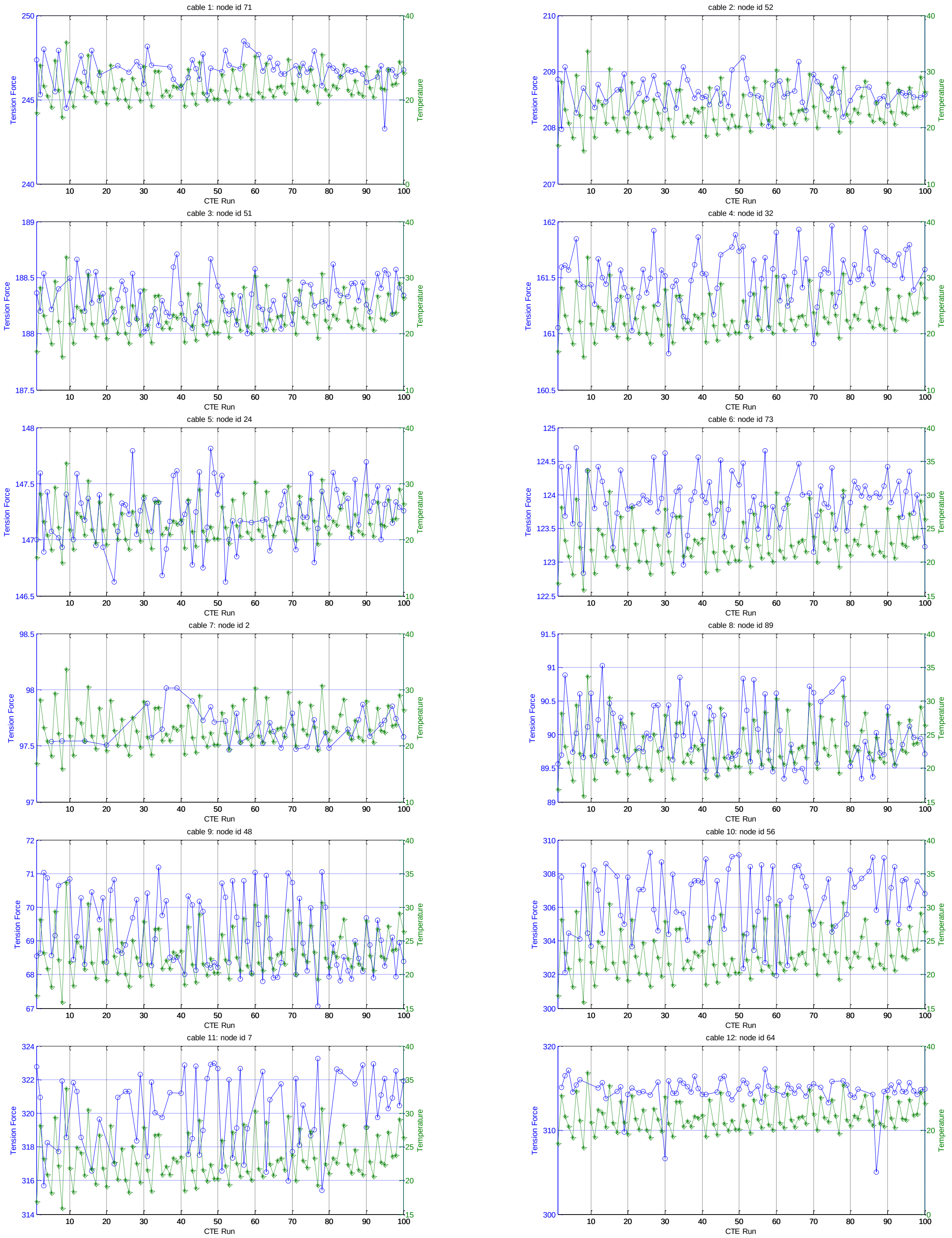

Figure 5. Cable tension forces estimated by the sensor network.

5. CONCLUSIONS

An autonomous wireless smart sensor network (WSSN) for cable tension monitoring was presented. A vibration-based method for cable tension estimation was selected and implemented on WSSN as an application called *CableTensionEstimation*. This application, based on independent processing, conducts sensing, estimates power spectrum of the measured response, performs autonomous peak-picking with curve-fitting to obtain natural frequencies, and calculates cable tensions that are subsequently sent to the base station.

CableTensionEstimation is used in the Jindo Bridge deployment in conjunction with *AutoMonitor*, a program that controls scheduling and sleep cycling for autonomous operation and efficient power management. Cable tensions have been successfully obtained autonomously using *CableTensionEstimation*. As the deployment on the cables is primarily focused on realization of the first autonomous WSSN for cable tension monitoring, the WSSN can be improved in both hardware and software aspects (e.g., cable tension algorithm that considers the cable sag, and improved fault tolerance). The Jindo WSSN has shown the potential of using smart sensor for autonomous, long-term monitoring of cable tension in cable-stayed bridges.

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