

Application of Wireless Monitoring System for the Ambient Vibration Study of the WuYuan Steel Arch Bridge

Y. Lei, W.A. Shen and Y. Song

Department of Civil Engineering, Xiamen University, China

J. P. Lynch

Department of Civil and Environmental Engineering, University of Michigan, U.S.A.

ABSTRACT: In this paper, the academic wireless monitoring system with smart sensing units developed at Stanford University and Michigan University is applied for the ambient vibration study of a steel arch bridge in Xiamen, China. Ambient acceleration responses of the bridge measured by the wireless sensing units are compared with those collected by a traditional wire-based data acquisition system. Clock synchronization performed by the wireless sensing network based on a centralized beacon signal is assessed. The local signal processing capacity of the smart sensors is also validated. Due to the low cost and easy installation advantages of the wireless sensing system, it is applied to the identification of modal properties of the bridge. Ambient acceleration responses of the bridge acquired by the wireless sensing units are used to identify the modal properties of the bridge based on the advanced stochastic subspace identification (SSI) method. It is shown that the ambient vibration data collected by the wireless monitoring system are accurate and these data can be applied to identify the dynamic properties of the bridge.

Keywords: wireless sensing, health monitoring, ambient vibration, modal properties

1 INTRODUCTION

Traditionally, structural monitoring systems employ coaxial wires to transfer measured data from sensors to centralized repository. Installation and maintenance of such wired-based monitoring system on large scale civil infrastructures, such as large span bridges, is time consuming and expensive, which limit widespread adoption of traditional monitoring systems. With recent development of wireless communication, wireless monitoring systems have been proposed to eradicate the extensive lengths of wires in the tethered systems (Spencer et al. 2006, Lynch et al. 2000, Lynch et al. 2006). Recently, some innovative academic and commercial wireless sensing systems have been developed (Lynch et al. 2006). Among them, the academic wireless sensing unit prototype developed at University of Michigan and Stanford University have received great attention as it emphasizes the design of a powerful computational core, low power consumption and multitasking capability (Lynch et al. 2005, Wang et al. 2006).

However, more validation studies on the performances of the wireless monitoring systems are essential before they can serve as economical substitutes to the traditional wire-based systems. Filed validation is the only way to accurately assess the performance of wireless monitoring systems within the complex and harsh environments posed by the real civil structures. In this paper, the performance of the wireless monitoring system devel-

oped at University of Michigan and Stanford University is validated through filed test on the Wuyuan steel arch bridge in Xiamen, China. As coaxial wires provide a very reliable communication link, a wire-based monitoring is also installed on the bridge for comparison. Acceleration responses of the ambient vibration of the bridge collected by the wireless monitoring system are compared with those obtained by the tethered system. The local computational capacity of the smart sensing units is also validated.

The dynamic characteristics, such as modal frequencies, mode shapes and modal damping values are important properties for the aerodynamic stability and health monitoring of bridges. Ambient vibration test combining with system identification algorithms provides a practical way to determine these dynamic characteristics of civil infrastructures. Due to the low cost and easy installation advantages of the wireless sensing system, it is applied to the identification of modal properties of the bridge. Of many existing system identification algorithms, the advanced stochastic subspace identification (SSI) method is used utilized in this paper as it is particularly useful when the number of outputs and the number of states (the order of the system) are relatively large. The identification of frequencies, mode shapes, and damping ratios for the Wuyuan Bridge is accomplished using ambient vibration measurements acquired by the wireless sensing units.

2 WIRELESS SENSING UNITS

As shown in Figure 1, the academic wireless sensing unit prototype developed at University of Michigan and Stanford University consists of three functional modules: sensor signal digitizer, computational core, and wireless communication module.

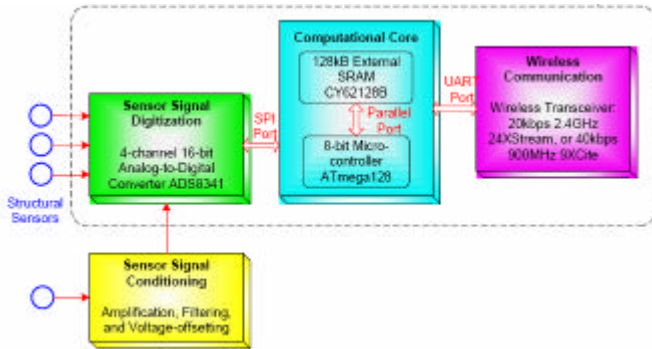


Figure 1. Hardware of the wireless sensing unit

The main component of the sensor signal digitization module is a 4-channel 16-bit A/D converter. Each wireless sensing unit can accommodate signals from a set of structural sensors, as long as their outputs are analog voltages from 0 to 5V. The computational core of the wireless unit is responsible for executing embedded software instructions for engineering analyses. A low-cost 8-bit microcontroller (Atmel ATmega128) is selected as the principle component of the computational core. The wireless sensing unit is designed to be operable with two wireless transceivers: 900MHz MaxStream 9XCite and 2.4GHz MaxStream 24XStream. This unique design feature is intended to allow users to employ the legal open-use frequency band in their regions.

As shown in Figure 1, before feeding the sensing signals into a wireless sensing unit, a signal conditioning printed circuit board may be applied. The three major functions of the circuit board are: offsetting, filtering and amplification.



Figure 2 Side view of the Wuyuan

3 WUYUAN BRIDGE

Wuyuan Bridge, with a total of 810m long and around 34m width, is an important bridge on the island ring road in Xiamen, China (Figure 2). The construction of the bridge was finished in 2003.

As shown in Figure 3, the 3-span main bridge is a half through basket type arch bridge consisting of steel-reinforced concrete girders and arch ribs. The main span is 210m long with two 58m side spans. The arch has a ratio of rise to span equal to 1/4 with a second-degree

parabola line shape. There are 9 strut rails on the arch to enhance the stability of the bridge in the transverse direction.

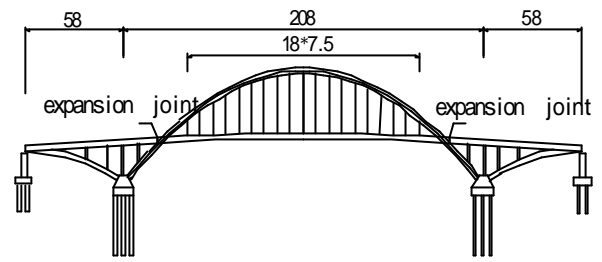
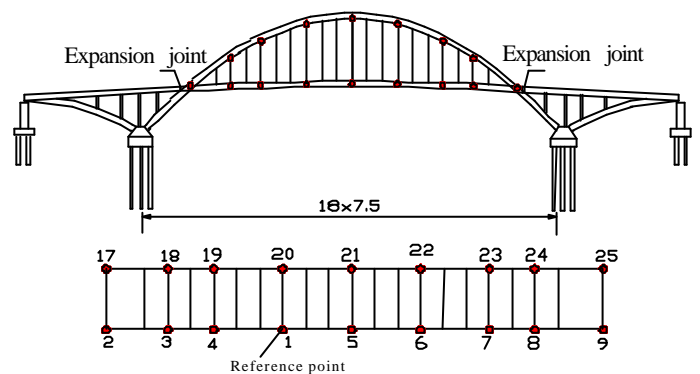


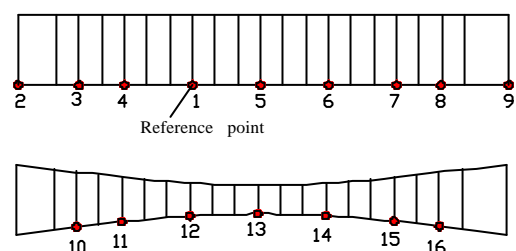
Figure 3 Side Elevation plan of the Wuyuan Bridge

4. INSTALLATION STRATEGIES

The wireless structural monitoring system developed at Stanford University and Michigan University is installed in the Wuyuan Bridge to monitor its ambient response. To validate its performance, a traditional tethered monitoring system is also installed, which allows the wireless monitoring system performance to be directly compared to that of the tethered system. Both the wireless and tethered structural monitoring systems employ accelerometers to measure the vertical and transverse responses of the bridge riders and arch ribs. The accelerometers are mounted in locations marked as # 1., 2., ..., 25 along the bridge riders and arch ribs, as shown in Figure 4. At each location, two accelerometers are aligned side-by-side as shown in Figure 5. They are connected to the wireless and tethered monitoring system, respectively (Figure 6). The distribution of the accelerometers is intended to provide ample data for the identification of bridge mode shapes.



(a) Locations of sensing units in the vertical direction



(b) Locations of sensing units in the transverse direction

Figure 4 Locations of sensing units on the girders and arch rib

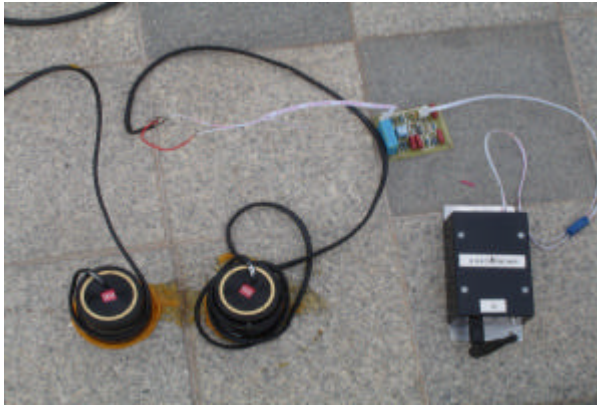


Figure.5 The wireless and wired-based sensing units

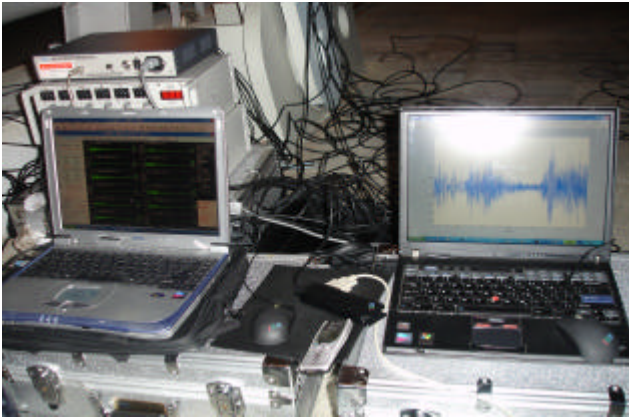


Figure 6. The wireless and tethered data acquisition system.

5. VALIDATION OF THE WIRELESS MONITORING SYSTEM

Since the wireless and tethered monitoring system do not start collecting data simultaneously, acceleration response time histories collected by the wireless sensing and tethered systems need to be shifted before comparison. Cross-correlation function of the two time histories of acceleration responses recorded by the two sensors aligned together can be used to determine the time shift of the acceleration time histories. As shown in Figure 7, the time-delay of the wireless sensing with respect to wired-based sensing can be estimated from the time lag of the peak value of the cross-correlation coefficient of the two time histories.

An important limitation of wireless monitoring systems is the absence of a centralized clock. Therefore, time synchronization is an important issue for wireless monitoring systems. The wireless sensing unit prototype used in this study is designed to synchronize its internal clock to a beacon signal broadcast from the centralized data repository. To validate the accuracy of the wireless sensing unit's time synchronization algorithm within a realistic structural environment, the time lags of wireless sensing units with respect to wired-based sensing units in each test are investigated. As the data from wired-based sensing are time-synchronized, the time lag of each wireless sensing can be used to check the accuracy of the unit's time synchronization. As shown in Table 1, all of the sensing units in the 5th test set have the same time lags. Thus, the data measured by wireless monitoring system in this test set are time synchronized. Similar results are obtained from other test sets. Therefore, beacon-based time synchronization algorithm in the wireless monitoring is quite effective

After shifting the time-history acceleration responses, the time-history acceleration responses of the wireless monitoring system are compared with those of the baseline tethered monitoring system. In Figure 8(a) and (b), time histories of acceleration recorded by the wireless sensing units at locations #1 and #24 are in close match with those by the traditional tethered systems. The minor differences between amplitudes of the time signals are due to the in-accurate amplification factors in the signal condition circuit boards. Figure 9(a-b) show the Fourier spectrum results determined from the time history data. Fourier frequency spectrum calculated from data by the wireless and tethered monitoring systems are also in good agreement.

One of the most attractive features of the wireless unit prototype used in this study is the sufficient on-board computational resources, e.g., the Cooley-Tukey implementation of the fast Fourier transform (FFT) is embedded in the computational core of the wireless sensing unit. After the frequency spectrum is calculated on-board, the values are wirelessly transmitted along with the raw time history response to the laptop data. To compare the accuracy of the embedded FFT analysis, the frequency spectrum is calculated offline by MATLAB using the raw time history response. As shown in Figure 10, the online FFT and offline FFT values are the same. The computa-

24XStream wireless transceiver operating at 2.4GHz, which is allowed in China, is used for wireless communication. Due to the limitation of bandwidth capacity, only 12 sensing units can simultaneously communicate data to the laptop when the data sampling rate is set to 50Hz, 5 vibration sets of tests are conducted to collect data from the sensors locations in Figure 4. These 5 sets of are described as;

1st set: Vertical dir. # 1, 2, 3, 10, 11, 12, 13;
Transverse dir.: #1, 10, 11, 12, 13;

2nd set: Vertical dir.: # 1, 8, 9, 14, 15, 16;
Transverse dir.: # 1, 14, 15, 16;

3rd set: Vertical dir.: # 1, 4, 5, 6, 7, 8;
Transverse dir.: # 1, 5, 7;

4th set: Transverse dir.: # 1, 2, 3, 4, 6, 8, 9;

5th set: Vertical dir.: # 1, 17, 18, 19, 20, 21, 22, 23, 24, 25;

As indicated, # 1 is used as the reference in the 5 test sets.

As these accelerometers output 0 V when there is no vibration, the signal condition circuit board are included in each wireless sensing unit to offset the sensor signals and to filter and amplify the weak and noisy ambient responses of the bridge. Amplification factor around 20x is used for each wireless unit.

tional core with embedded engineering analysis avoids the transmission of a large amount of raw time history data, which is power efficient for a wireless monitoring system.

6. IDENTIFICATION OF THE DYNAMIC PROPERTIES OF THE BRIDGE

Ambient vibration test combining with system identification algorithms provides a practical method for the determination of the dynamic characteristics of civil infrastructures. One of the attractive feature of the wireless sensing system is its low cost and easy installation. Thus, it can be applied for the identification of modal properties of the bridge.

The stochastic subspace identification (SSI) provides a very effective algorithm to identify the mode shapes of the structures through the spatially distributed sensors. Thus, it is used for the identification of the bridge based on the ambient acceleration responses time histories collected by the wireless sensing units along the bridge girders and arch ribs as indicated in Figure 4. The identified frequencies and damping ratios values of the first 7 vibration modes of the bridge are summarized in Table 2. The corresponding first mode shapes are shown in Figures 11(a)-(c). It is noted that the fundamental frequency of the bridge is 0.776 Hz, which corresponds to a bending motion of the bridge and arch in the vertical direction. The motions of arch and bridge girders are coupled together. These are in good agreements with those evaluated by previous engineers after the bridge was constructed.

7. CONCLUSIONS

The academic wireless monitoring system with smart sensing units developed at Stanford University and Michigan University is validated through ambient vibration test on Wuyuan the steel arch bridge in Xiamen, China. Ambient acceleration responses of the bridge measured by the wireless sensing units are in close match with those collected by a traditional wire-based data acquisition system. Clock synchronization performed by the wireless sensing network based on a centralized beacon signal is assessed to be accurate. The local signal processing capacity of the smart sensors is also validated.

Due to the attractive feature of low cost and easy installation of wireless sensing system, installation of a dense sensing array on bridge is not a time consuming and labor intensive issue. Therefore, the wireless monitoring system can be applied to the identification of the modal properties of the bridge. The stochastic subspace identification (SSI) provides a very effective algorithm to identify the modal frequencies, modal damping ratios and mode shapes of the bridge based on the ambient vibration data of acceleration responses. The identified modal properties are in good agreements with those evaluated by engineers after the bridge was constructed.

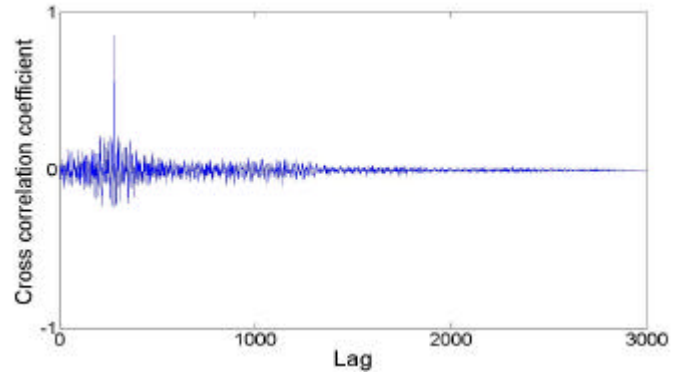


Figure 7: Cross- correlation coefficient between wireless and wire sensing

Table 1. Time synchronization of the wireless sensing units (Test 5)

| Sensor Location | Time lag | Time Delay |
|-----------------|----------|------------|
| # 1 | 281 | 0 |
| #18 | 281 | 0 |
| #19 | 281 | 0 |
| #20 | 281 | 0 |
| #21 | 281 | 0 |
| #22 | 281 | 0 |
| #23 | 281 | 0 |
| #24 | 281 | 0 |

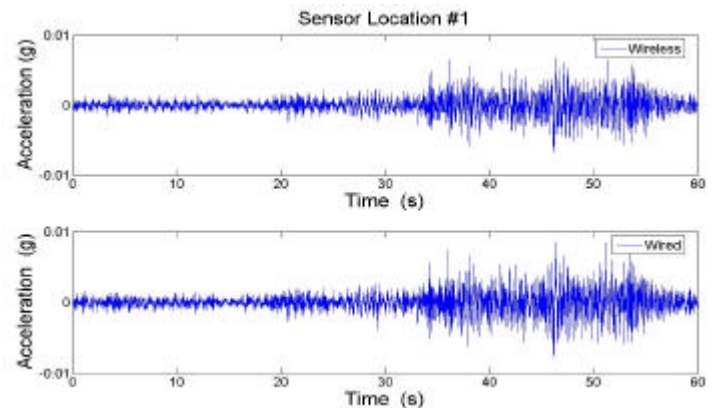


Figure 8(a) Comparisons of acceleration time history at sensor location No.1

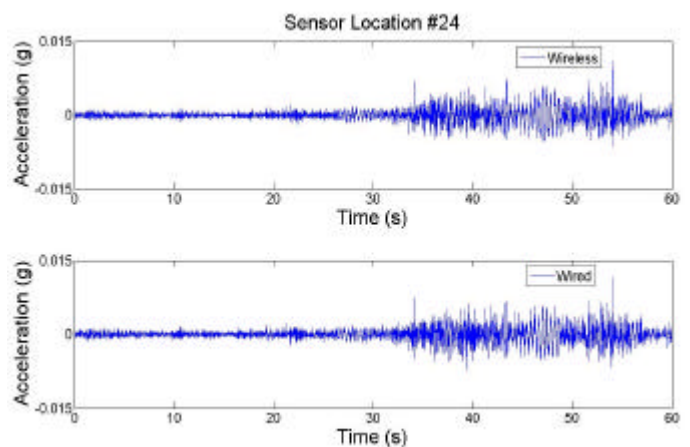


Figure 8(b) Comparisons of acceleration time history at sensor location No.24

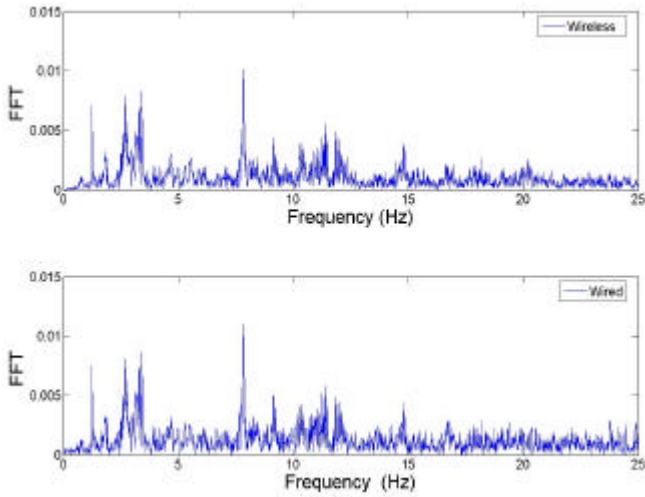


Figure.9 (a) Location #1, Comparisons of Corresponding Fourier Spectrum ,The wireless system (Top) and Wire system (Bottom)

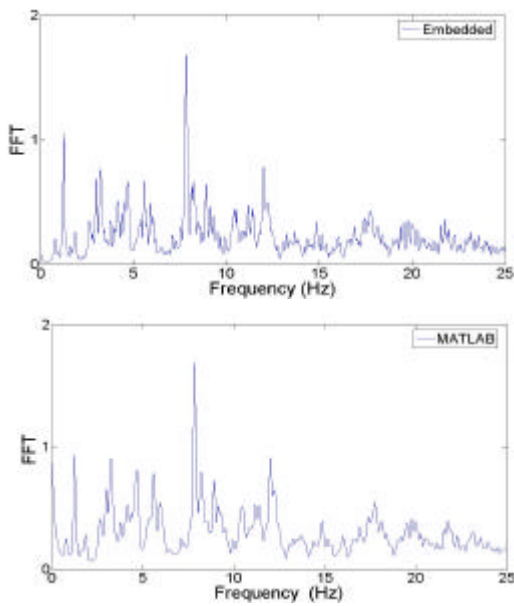


Figure.10 Comparison of Online (Top) and Off-Line (Bottom) FFT, Response corresponds to sensor Location #5

Table2. Modal Identification of Wu Yuan Bridge by SSI

| Mode | Frequency (Hz) | Damping Ratio (%) | Mode Shape Description |
|------|----------------|-------------------|------------------------|
| 1 | 0.7756 | 2.572 | 1st Vertical Bending |
| 2 | 1.230 | 1.363 | 1st Transverse Bending |
| 3 | 1.242 | 0.653 | 2nd Vertical Bending |
| 4 | 1.698 | 1.256 | 3rd Vertical Bending |
| 5 | 1.837 | 3.968 | 1st Torsion |
| 6 | 2.431 | 0.692 | 2nd Torsion |
| 7 | 2.712 | 3.221 | 2nd Transverse Bending |

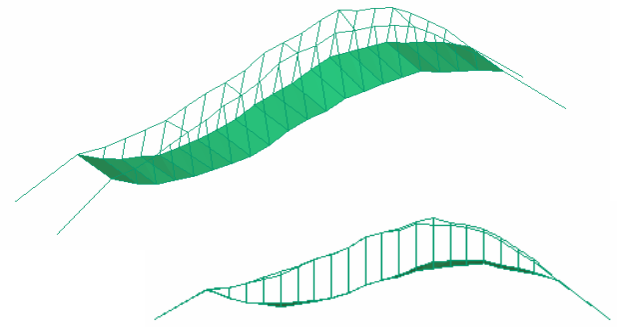


Figure.11 (a) First Mode Shape, $f=0.7756$ $\zeta=2.572$

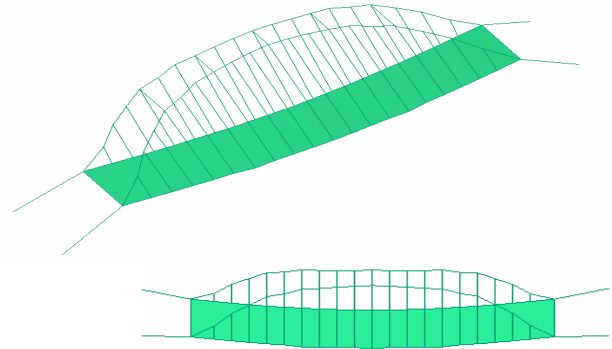


Figure.11 (b) 2nd Mode Shape, $f=1.230$ $\zeta=1.363\%$

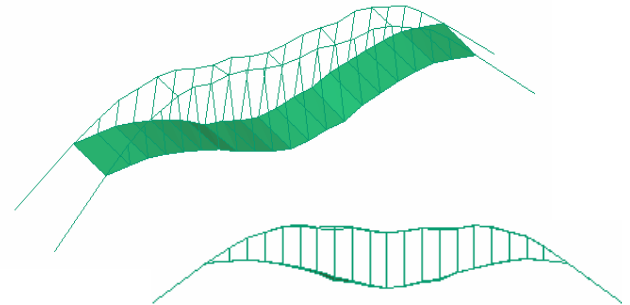


Figure .11 (c) 3rd Mode Shape $f=1.242$ $\zeta=0.6533\%$

ACKNOWLEDGEMENT

This collaborative research is funded by grants from China and USA. The Authors acknowledge support from the Science and Technology Project of Fujian Province through Grants Nos. 2005YZ1021 and the program for Bureau of Xiamen Construction Management (No. 2006-11). support from the National Science Foundation Grant Number CMMS-0528867

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