A prototype mobile sensor network for structural health monitoring

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ABSTRACT

Wireless sensing has been widely explored in recent years for structural monitoring and dynamic testing. The limitations of current wireless sensor networks have been identified with regard to limited power supply, communication bandwidth, communication range, computing power, etc. The cost of most wireless structural sensors is still prohibitive for dense instrumentation on large civil structures. To address the above challenges, this research proposes a new methodology for structural health monitoring based upon mobile sensor networks. In this research, prototype mobile sensing nodes have been developed using magnet-wheeled cars as the sensor carriers. These mobile sensing nodes can maneuver upon structures built with ferromagnetic materials. Performance of the prototype mobile sensing system has been validated on a laboratory steel frame. Modal analysis for the frame structure is conducted using the data collected by the mobile sensing nodes. This exploratory work illustrates the flexible spatial resolutions offered by mobile sensors, which represent a transformative change from the fixed spatial resolution provided by traditional static sensors.

Keywords: mobile sensor networks, wireless sensors, structural health monitoring, modal testing.

1. INTRODUCTION

As civil structures are continuously subjected to various static and dynamic loadings, as well adverse environmental effects, their safety conditions may deteriorate rapidly. For example, more than half of the bridges in the United States were built before 1940's, and nearly 42% of them were reported to be structurally deficient and below established safety standards [1]. To protect the public from unsafe bridge structures, current U.S. federal highway administration requests local transportation authorities to visually inspect the entire inventory of over 580,000 highway bridges. Due to limited resources, current inspections can only be conducted once every two years. Furthermore, visual inspections can only identify damage that is visible on the structure surface; damage located below the surface often remains elusive to the inspectors. As a result, there is a pressing need for reliable structural monitoring systems that can automatically and quantitatively assess the real-time condition of civil structures.

In recent years, structural health monitoring technologies have attracted much research interest as a complimentary approach and promising alternative to visual structural inspections. A structural health monitoring (SHM) system measures structural performance and operating conditions with various types of sensing devices, and evaluates structural safety conditions using certain damage diagnosis or prognosis methods [2, 3]. Among the many advances in SHM research, "smart" wireless sensors capable of embedded computing and wireless communication have attracted much interest. Wireless communication in SHM systems was originally proposed to significantly reduce the monetary and time cost for installing lengthy cables in a SHM system [4]. Sensors incorporated with wireless communication can exchange information with each other, network hubs, or a base station. In recent years, a great amount of research efforts has been dedicated into the development of wireless sensing systems for structural health monitoring. A comprehensive review of wireless sensors and their adoption in structural health monitoring has been provided by [5]. For example, the wireless SHM platform designed by Wang *et al.* [6] has been successfully validated on a number of

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bridges, buildings, and wind turbines located in the US, Taiwan, South Korea, China, and Germany [7-9]. In addition, the functionality of the wireless units has been extended for real-time feedback control of civil structures [10].

As a transformative change to wireless sensor networks, the next revolution in sensor networks has been predicted to be mobile sensor networks that implant mobility into traditional sensor networks [11, 12]. In a mobile sensor network, each mobile sensing node can be an autonomous robot equipped with one or multiple smart sensors. The mobile node explores its surroundings and exchanges information with its peers through wireless communication. The mobility of autonomous robots resolves some most critical challenges faced by static wireless sensor networks [13]:

1) Due to the high complexity of large civil structure systems, the location where damage occurs can be largely unpredictable. In order to closely monitor the structure, static wireless sensors usually need to be deployed at a very high density. However, the cost and difficulty associated with dense arrays of wireless sensors are still prohibitive for wide deployment in practice. On the other hand, mobile sensor networks offer flexible architectures, which lead to adaptable spatial resolutions that are unavailable from static wireless sensors.

2) Limited power supply is one of the largest constraints for wireless sensor networks, while current energy harvesting techniques cannot yet provide a reliable, convenient, and low-cost solution for powering typical wireless structural sensors [14, 15]. This constraint is eliminated in mobile sensor networks, if the mobile sensing nodes can periodically return to a base station for automatic recharging.

3) For mobile sensor networks, reduced power constraint means that powerful microprocessors can be adopted to execute more sophisticated damage detection algorithms; it also means that more options for wireless transceivers exist for higher data rate, longer transmission range, and better synchronization accuracy.

Motivated by the interest to incorporate mobility into traditional sensors, a few inspection robots have been developed for SHM. For example, a robot able to crawl on a 2D surface was developed for visually inspecting aircraft exterior; the robot used ultrasonic motors for mobility and suction cups for adherence [16]. A beam-crawler has been developed for wirelessly powering and interrogating battery-less peak-strain sensors; the crawler moves along the flange of an I-beam by wheels [17]. Based upon magnetic on-off robotic attachment devices, a magnetic walker has been developed for maneuvering on a 2D surface [18]. Most recently, a remotely-controlled model helicopter has been illustrated for charging and communicating with wireless sensors [19]. To the best of our knowledge, mobile sensor networks with dynamic reconfiguration have rarely been explored by researchers for SHM purpose. In addition to structural damage detection, recent needs to inspect aging pipelines have also motivated a flurry of research to develop locomotion systems (based on wheels, tracks, legs or arms) combined with an attachment system (such as grasps, suction cups, adhesive polymers or magnetic elements) for maneuvering in different pipe environments [20, 21].

The environment considered in this study is a complex civil structure with narrow sections, high abrupt angle changes, inclined elements, and underside surfaces. Such environment requires compact mobile nodes with 3D climbing ability, as well as a high degree of mobility for negotiating obstacles. In this preliminary work, we have identified magnet-wheeled robots as a feasible approach for maneuvering upon structures built with ferromagnetic materials. This paper describes such a prototype mobile sensor network developed for structural health monitoring, as well as the validation experiments conducted in the laboratory. The mechanical, hardware, and software design of the mobile sensing node is first described in Section 2. Results from laboratory validation experiments are demonstrated in Section 3. In the experiments, a four-node mobile sensor network is used to collect vibration data of a steel portal frame at a high spatial resolution; modal analysis for the steel frame is conducted using the mobile sensor data.

2. DESIGN OF A PROTOTYPE MOBILE SENSING NODE

Fig. 1 illustrates the functionality diagram of the prototype mobile sensing node. The design of such a mobile sensing node entails efforts in areas such as mechanical, hardware, and software. A previously developed wireless sensing unit is adopted as the key component of this mobile sensing node. The wireless sensing unit consists of three functional modules: sensor signal digitization, computational core, and wireless communication. Detailed description of the wireless sensing unit can be found in [6]. In the mobile sensing node, a new mobility module is incorporated. Major components of the mobility module include the servo motors and magnet wheels. To allow the mobile sensing node move safely on the underlying structural surface, motion of the node is monitored by boundary detection sensors. This

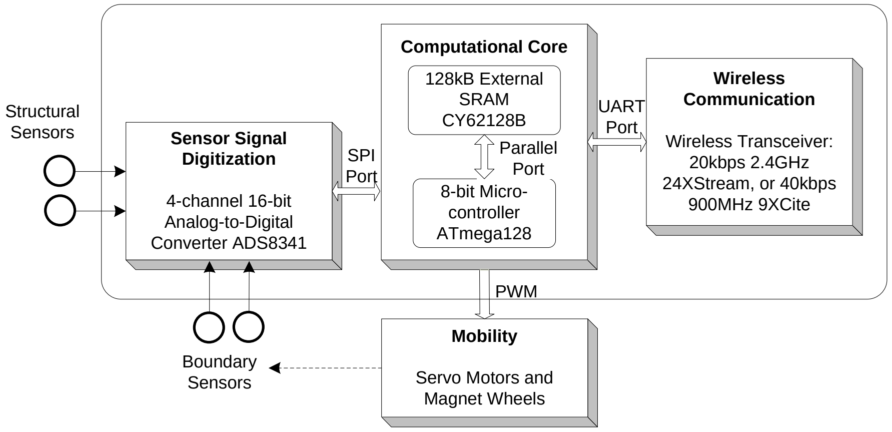


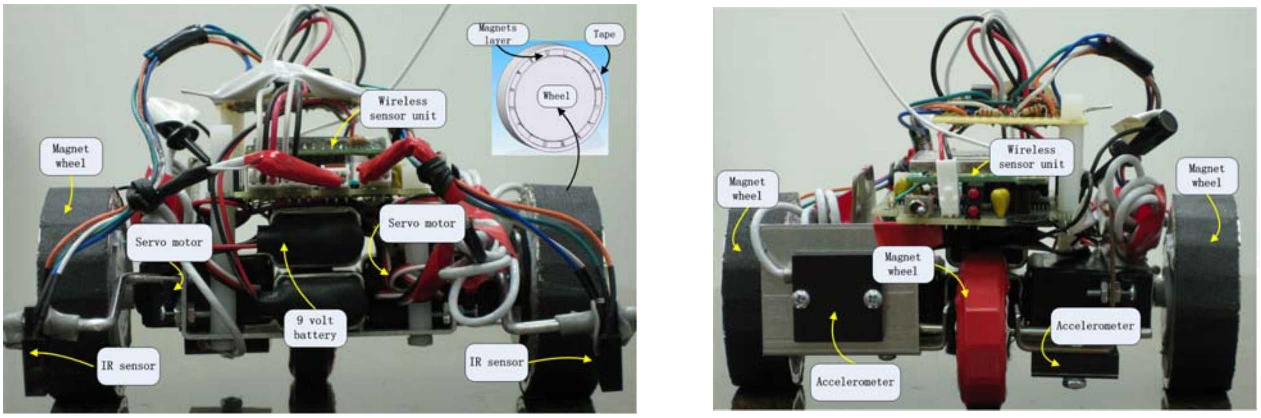
Fig. 1. Functional diagram of the prototype mobile sensing node.

section first introduces the mechanical design of the prototype mobile sensing node, and then describes the hardware and software design.

2.1 Mechanical design

Fig. 2(a) shows the front view of the prototype mobile sensing node capable of moving on structures built with ferromagnetic materials; Fig. 2(b) shows the back view. Physical components of the mobile sensing node include the body frame, wheels, motors, batteries, a wireless sensing unit [6], and sensors with associated hardware circuits. The width of the mobile sensing node is about 6 in, the height 3.6 in, and the length 4.7 in. The total weight of the mobile sensing node is slightly over 1 lb, most of are due to the magnet wheels, motors, and batteries.

The mobile sensing node maneuvers with two motorized side wheels (shown in Fig. 2(a)) and one passive middle wheel (shown in Fig. 2(b)). The perimeters of all three wheels are surrounded with thin magnet blocks that provide enough attraction forces between the wheels and the surface of the underlying ferromagnetic structures. The magnet blocks are magnetized along the thickness direction. Two 9V batteries are placed between the servo motors, one battery powering both motors, and the other battery powering the electronic circuits. An infrared (IR) sensor is installed at each side of the mobile sensing node for detecting the boundaries of the underlying structural surface. Two accelerometers are



(a) (b)

Fig. 2. Pictures of a prototype mobile sensing node: (a) front view; (b) back view.

attached on the body frame of the mobile sensing node. The Silicon Design 2012 accelerometer shown in the lower left part of Fig. 2(b) measures the horizontal vibration, and accelerometer shown in the lower right part of Fig. 2(b) measures vertical vibration (with respect to the local coordinates of the mobile sensing node). The authors are currently developing a mechanism to firmly attach an accelerometer onto a structural surface during data collection, and retrieve the accelerometer afterwards.

2.2 Hardware and software design

In the mobile sensing node, components in the previously developed wireless sensing units now assist in providing mobility. For example, the wireless communication link is utilized for sending motion commands to the sensor node from a computer server; similarly, the microcontroller of the wireless sensing unit is responsible for executing the motion commands and ensure safe maneuver of the mobile node on a structure surface. As shown in Fig. 1, the microcontroller commands the servo motors with pulse-width modulation (PWM) signals generated through the timer interrupt functions. The speed and direction of each motor is controlled by the duty cycle of the associated PWM signal. To allow the mobile sensing node move safely on the underlying structural surface, two IR sensors are adopted for surface boundary detection. The IR sensors are placed at the two sides of the body frame. In each IR sensor, an emitting diode emits infrared radiation, and a detection diode detects the radiation reflected from the structural surface. When a side wheel of the mobile sensor is moving outside the surface boundary, changes can be captured from the reflected IR signal. Consequently, the microcontroller immediately sends command signals to the motors for speed adjustment, so the two driving wheels collaboratively maintain the mobile sensing node within the surface boundaries.

To allow the embedded software to be used for both wireless sensing and nodal mobility, state machines for the wireless sensing software is modified. The modification is shown in bold font in Fig. 3. When the mobile sensor is powered on, it will automatically initialize the memory space and transit into “State 1”. When it receives “18PrepareToMove” command, it will send command “08AckStart” to the server and stay in “State 4”. In “State 4”, the mobile sensor can move or stop, according to the command received from the server. The mobile sensing node can also detect out-of-boundary conditions using the IR sensors, and adjust the speeds of two motors accordingly. If “10Restart” command is received, the node transits back to ”State0” and then “State 1”, so that commands for wireless sensor data acquisition can be processed properly. The server side software is also modified for sending motion control commands to the wireless sensor nodes.

3. LABORATORY EXPERIMENTS

Laboratory experiments are conducted to validate the performance of the prototype mobile sensing node. This section

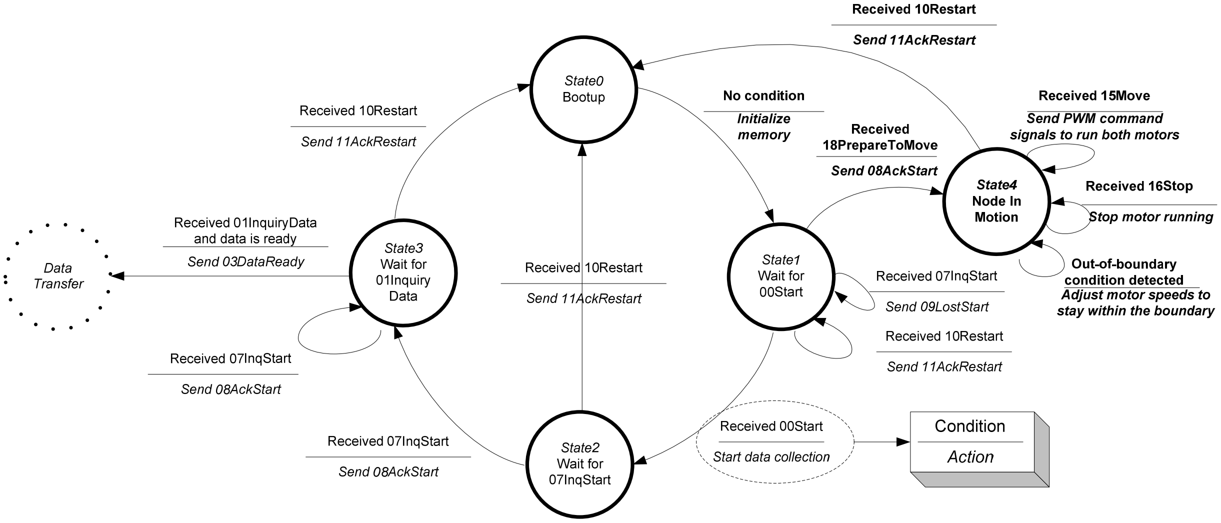


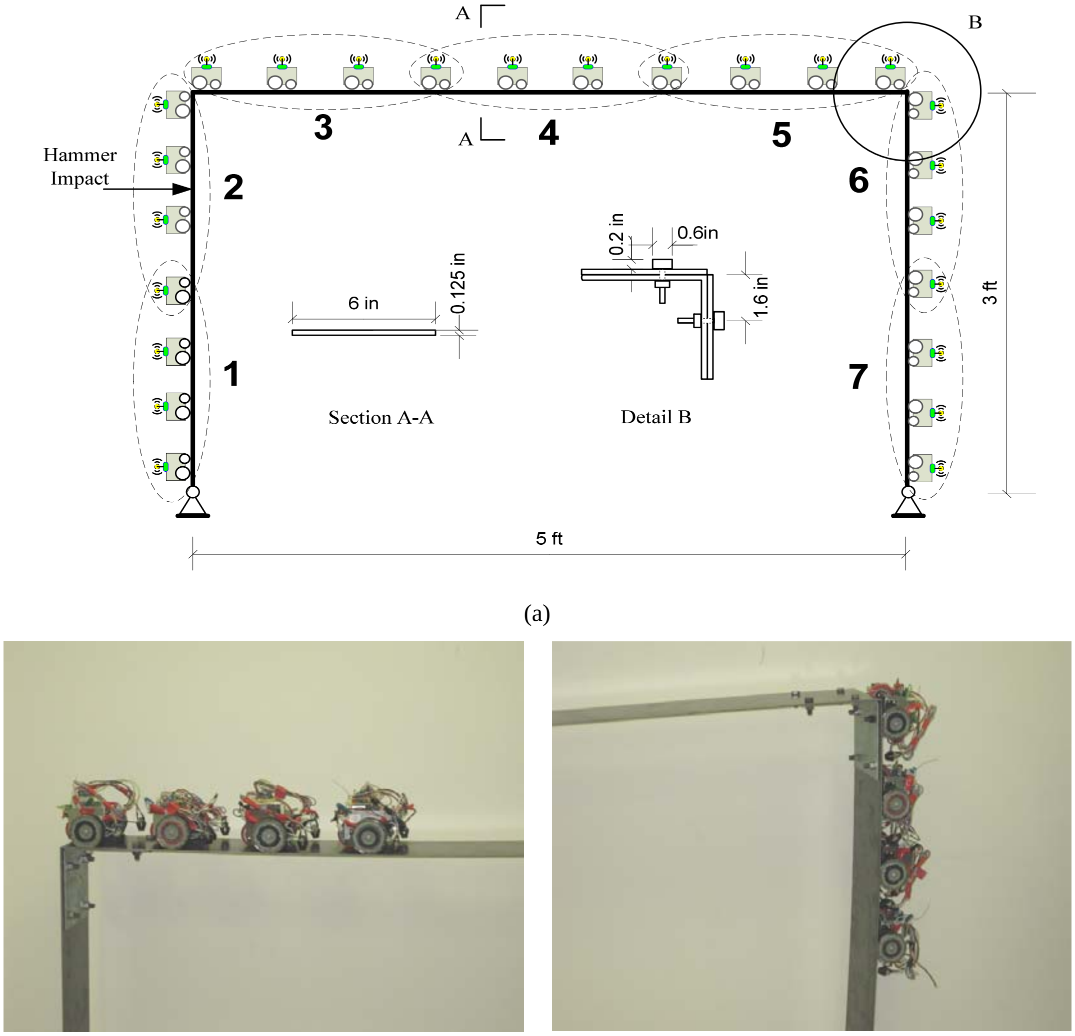
Fig. 3. Simplified state diagram for a mobile sensing node.

describes the experimental setup, as well as the structural modal analysis using the mobile sensor data.

3.1 Experimental setup

A 2D laboratory steel portal frame structure is constructed for validating the performance of the mobile sensing nodes (Fig. 4(a)). The span of the portal frame is 5 ft, and the height is 3 ft. The beam and two column members have the same rectangular section area of 6 in × 1/8 in. The orientation of the members allows the thickness (1/8 in) side of the sections to be observed from the view angle in Fig. 4(a). Hinge connections are constructed at the bases of the two columns; the beam and the columns are connected by bolted angle plates.

Fig. 4(a) also illustrates the seven configurations for the mobile sensor network. In configuration #1, all four mobile nodes are located near the base of the left column; in configuration #2, all four nodes move up to the upper part of the column, and so on. One overlapping location is allocated between every two neighboring configurations, so that the overall structural vibration mode shapes can be assembled using results from the seven configurations. Fig. 4(b) shows four prototype mobile sensing nodes deployed in configuration #3, and Fig. 4(c) shows the nodes deployed in



(a)

(b)

(c)

Fig. 4. 2D steel portal frame for mobile sensor testing: (a) diagram showing the configurations of mobile sensing nodes; (b) four mobile sensing nodes at the left end of the beam, i.e. configurations #3; (c) four mobile sensing nodes at the upper end of the right column, i.e. configuration #6.

configuration #6.

The width of the structural members is slightly larger than the width of the prototype mobile sensing node. In response the out-of-boundary signals from the IR sensors, speed adjustments to the motors are first refined to make the mobile sensing node move safely along the beam or the two columns. Because the magnetic attraction force reduces to the minimum when the wheels move around a beam/column corner, the challenge appeared to be making the mobile sensing node capable of transiting from the columns to the beam, and vice versa. After some iterative improvements to the magnet wheel design and the associated embedded software, the mobile sensing node can reliably climb over the beam-column connections of this steel frame. Fig. 5 shows the magnet wheeled robot transiting from the left column to the beam.

3.2 Measurement results from mobile sensors

In the current prototype, two accelerometers are mounted on the body frame of the mobile sensing node. Therefore, it is necessary to observe the influence of the body frame vibration to the acceleration data. Experiments are conducted to compare the data collected by the mobile sensing nodes and static sensors (Fig. 6). In these experiments, a static sensor is mounted at the same location as a mobile sensing node. After a hammer impact, data from the mobile sensing node

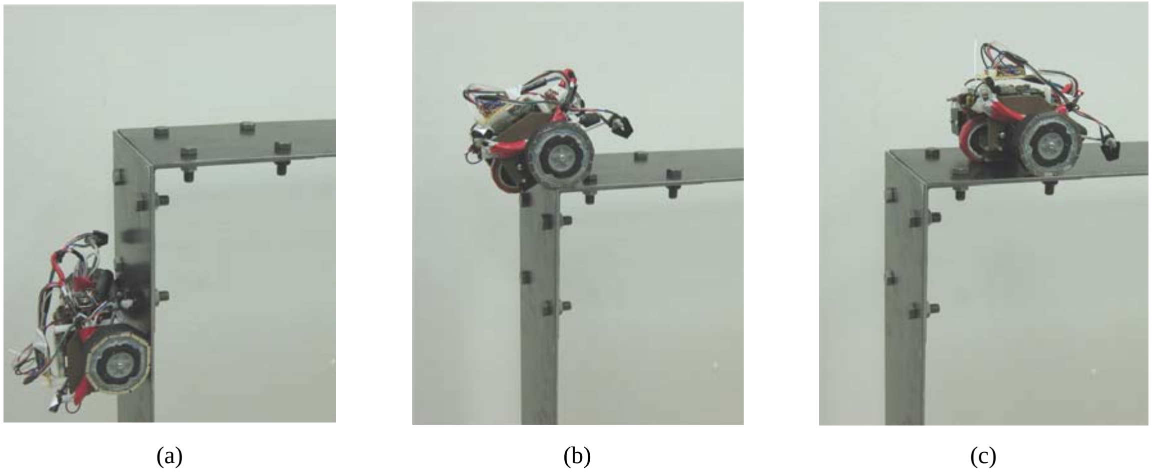


Fig. 5. A prototype magnet-wheeled mobile sensing node transiting over the beam-column connection of the laboratory steel frame: (a) on the column; (b) at the corner; (c) on the beam.

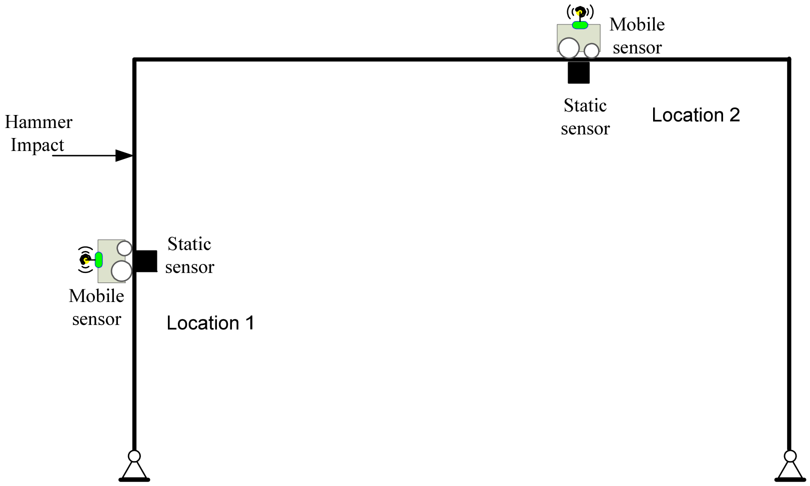
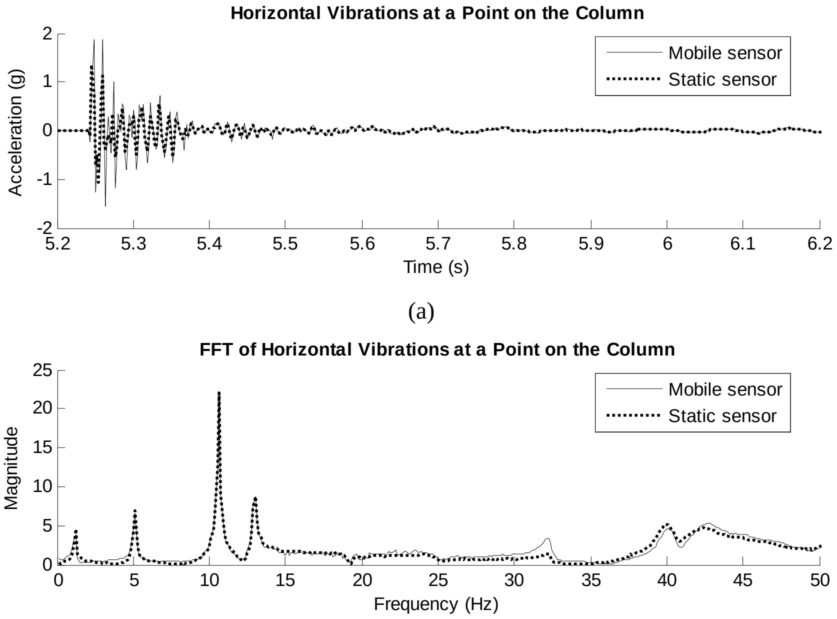


Fig. 6. Comparison between static and mobile sensor data at two locations.

and the static sensor are both collected.

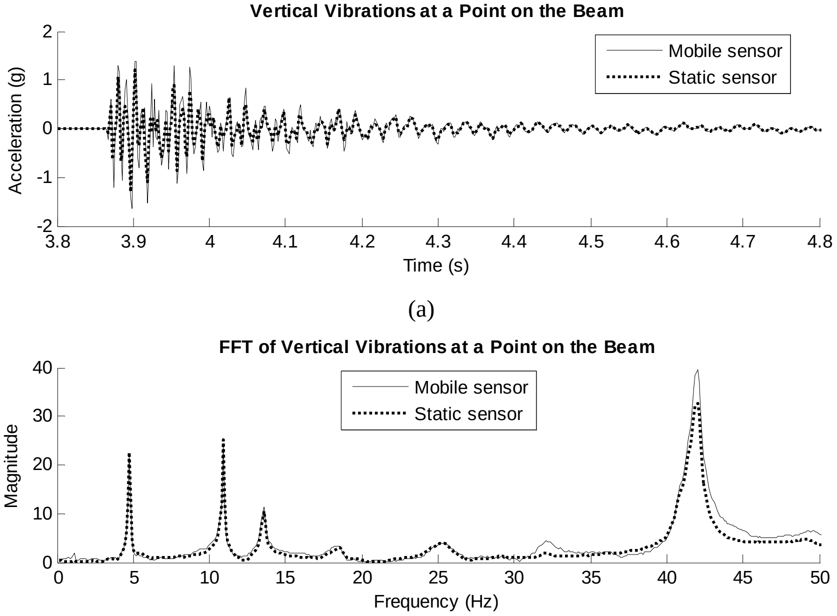
Fig. 7(a) illustrates the comparison between mobile sensor data and static sensor data, when both sensors are mounted at location 1 in Fig. 6, and an impact hammer is used to hit the left column. Fig. 8(a) illustrates a similar comparison where both the mobile sensing node and a static sensor are mounted at location 2 in Fig. 6, and the impact hammer is used to hit the same point on the column. A sampling frequency of 500Hz is used for the mobile and static sensor data



(a)

(b)

Fig. 7. Comparison between data measured by a mobile sensor and a static sensor mounted on the left column: (a) time history data; (b) FFT results.



(a)

(b)

Fig. 8. Comparison between data measured by a mobile sensor and a static sensor mounted on the beam: (a) time history data; (b) FFT results.

collection. The two figures show that the mobile sensor data is very close to the static sensor data, especially a few seconds after the hammer impact. The difference is slightly larger immediately after the hammer impact, when the structural vibration contains more higher-frequency components that dissipate quickly. Dynamics of the magnet-wheeled car has little influence to lower-frequency vibration measurements, while may have more influence to higher-frequency measurements. The difference between the mobile and static sensor data in frequency domain is illustrated in Fig. 7(b) and Fig. 8(b). Relatively sharp peaks around the first few natural frequencies are observed for both data sets. It can be seen that in lower frequency domain, there is less difference between the mobile sensor data and the static sensor data.

3.3 Modal analysis using mobile sensor data

Using data collected by the mobile sensor data due to hammer impact excitations, modal analysis for the steel frame is conducted. Mode shapes for different configurations are conducted individually, and then the shapes are assembled using the overlapping points between neighboring configurations (Fig. 4(a)). The first four natural frequencies of the structure are identified as 1.09Hz, 4.75Hz, 10.19Hz, and 13.05Hz. As shown in Fig. 9, the high spatial resolution offered by mobile sensing nodes enables modal analysis with smooth mode shapes. These mode shapes are very close to

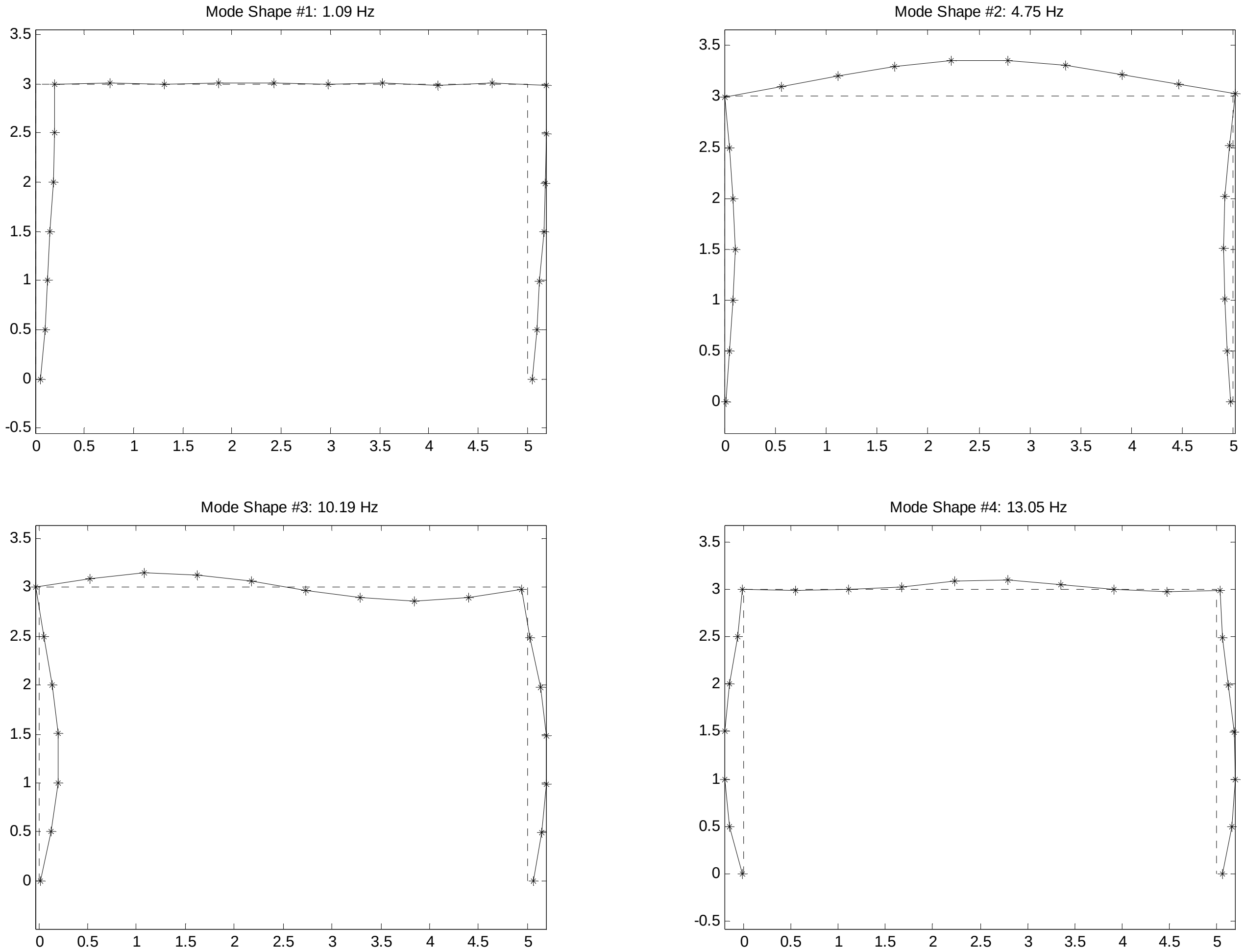


Fig. 9. First four vibration mode shapes identified using mobile sensor data.

the results from a high-resolution Finite Element analysis. Note that in this work, the modal analysis neglects the influence from the mass of the mobile sensing nodes to the dynamics of the steel frame. Future design of the mobile sensing nodes will aim at lighter, smaller, and more agile nodes that will have less influence to structural mass. Compared with the weight of real-world civil structures, such as steel bridges or wind turbine towers, masses of the mobile sensing nodes should have limited influence to the structural dynamics. Given that a reliable sensor attachment and retrieval mechanism is developed later, another possible solution to the mass influence problem is to let the mobile sensing node stay away form the measurement zones while vibration data is being sampled.

4. SUMMARY AND DISCUSSION

Exploratory work in using mobile sensor networks for structural health monitoring is presented in this paper. Although the work is preliminary, the effectiveness of mobile sensors in providing measurements with high spatial resolution is illustrated. The prototype mobile sensing nodes can reliably maneuver upon the laboratory steel portal frame. High-fidelity sensor data is collected using the four mobile sensing nodes; modal analysis is successfully conducted for the steel portal frame. It is envisioned that mobile sensor networks will offer flexible and adaptive spatial resolutions that can greatly advance future theory and practice in structural health monitoring and damage detection.

Improvements to the prototype mobile sensor network will be devoted into a number of areas. First, the authors are currently developing a mechanism for firmly attaching accelerometers onto structural surface, so that the influence from the body dynamics of the mobile sensing node can be eliminated in the acceleration measurements. Harnessing the embedded computing power of the mobile sensing nodes, research will also be conducted to enable the mobile sensing nodes with the capabilities of autonomously detecting potential damages in the structure. Last but not least, a great amount of efforts will be needed to make the mobile sensing nodes capable of maneuvering upon real-world structures built with ferromagnetic materials.

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