COVER SHEET

Title: *Flexure-based Mechatronic Mobile Sensors for Structure Damage Detection*

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ABSTRACT

Wireless sensing has been widely explored in recent years for structural monitoring and dynamic testing, due to its advantage in reducing instrumentation time and cost. Limitations of current wireless sensors have been identified in terms of power supply, communication bandwidth, communication range, computing power, etc. To address the above challenges faced by traditional wireless sensor networks with static configurations, this research proposes a new approach for structural health monitoring using mobile sensor networks. Compared with static wireless sensors, mobile sensor networks offer flexible system architectures with adaptive spatial resolutions. This paper describes the design concept of a flexure-based mechatronic (flexonic) mobile sensing node. The flexonic mobile sensing node is capable of maneuvering on structures made of ferromagnetic materials, as well as attaching/detaching the accelerometer on/from the structural surface. Concept feasibility of the flexonic mobile sensing system has been validated in a laboratory setting. Numerical simulations are conducted to explore the effectiveness of transmissibility function analysis in detecting potential damage in the laboratory steel portal frame.

INTRODUCTION

Due to various adverse operational and environmental conditions, a civil structural system may deteriorate rapidly through its lifespan. For example, according to the ASCE 2009 report card for America's infrastructure, more than one in four of the bridges in the United States were categorized as structurally deficient or functionally obsolete. In order to improve the safety assessment for civil structures, extensive research has been performed in the field of structural health monitoring

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(SHM). Among many new technologies developed for SHM, wireless sensing has been widely explored in recent years. Compared to conventional cable-based systems, wireless systems have the advantage of significantly reducing instrumentation time and cost. An exhaustive review on wireless sensing for SHM can be found in [1].

As a transformative change to wireless sensing, the next revolution in sensor networks is predicted to be mobile sensing systems containing individual mobile sensing nodes [2]. Each mobile sensing node can explore its surroundings and exchange information with its peers through wireless communication. A mobile sensing system offers measurement data with adaptive spatial resolution. Furthermore, mobile sensors may automatically recharge at a base station, which alleviates the power constraints with static sensors [3]. In various applications, efforts have been made in incorporating mobility into traditional sensors. For example, a robot using ultrasonic motors for mobility and suction cups for adherence to crawl on a 2D surface was developed for visually inspecting aircraft exterior [4]. 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 [5]. Based upon magnetic on-off robotic attachment devices, a magnetic walker has been developed for maneuvering on a 2D surface [6]. In order to inspect the inner casing of ferromagnetic pipes with complex-shaped structures, a compact robot with two magnetic wheels in a motorbike arrangement has been developed [7]; the robot can slightly lift off the wheel in order to negotiate concave edges. Nevertheless, there is a need for a mobile platform that can climb upon 3D civil structures and obtain various sensor data for SHM.

In recent years, many vibration-based damage detection methods have been developed. Among these methods, analysis based upon transmissibility function (TF) attracted much research interests due to its effectiveness in damage identification, as well as because the analysis does not require measuring input forces. Different aspects that may affect TF analysis have been explored, such as the linearity of structures [8], the nature of input forces [9], and operational and environmental variability effects [10]. Based upon previous research, TF analysis is well understood, and is being widely investigated in dynamic testing.

This paper introduces a prototype mobile sensing system for SHM. The mobile sensing node is designed for negotiating in complex steel structures with narrow sections, high abrupt angle changes, inclined elements, and underside surfaces. In a prior design [11], accelerometers on the mobile sensing node are not in direct contact with the structure; therefore, higher frequency components cannot be captured for detecting local damage. To improve the performance of the previous prototype, a new design concept of a flexonic (flexure-based mechatronics) mobile sensing node is discussed in [12]. As a continuing effort, this paper presents the implementation of the flexonic mobile sensing node that has the ability of attaching/detaching sensor on/from the structure surface.

The paper begins with the mechatronic hardware and software implementation of the flexonic mobile sensing node. Validation experiments for the mobile sensing node are then presented. Finally, numerical simulations using transmissibility function analysis to detect potential damage in the laboratory portal frame are described (in preparation for future experiments on structural damage detection using mobile sensing data).

DESIGN OF A FLEXONIC MOBILE SENSING NODE

Mechanical Design

Fig. 1 shows the prototype flexonic mobile sensing node consisting of three substructures: two 2-wheel cars and the compliant connecting beam. The design analysis of the flexure-based mobile node is described in [12]. Each 2-wheel car contains a body frame, motors, batteries, a wireless sensing unit [13], as well as IR sensors and Hall-effect sensors with associated hardware circuits. The flexonic mobile sensing node maneuvers with four motorized wheels. The wheel is surrounded by thin rectangular magnets to provide attraction between the wheels and the surface of the underlying ferromagnetic structure, along which the magnets are magnetized. Two 9V batteries are placed on each 2-wheel car; one powers motors and the other powers the electronic circuits. The wheel rotation is measured by a Hall-effect sensor, while the boundaries of the underlying structural surface are detected by a pair of IR sensors.

An accelerometer (manufactured by Silicon Designs, Inc.) is mounted at the middle of the compliant beam between the two 2-wheel cars. The accelerometer can be attached by bending the compliant beam onto the surface for measuring structural vertical vibration, and detached from the surface by straightening the compliant beam after measurement. The width of the flexonic mobile sensing node is about 0.152m (6 in), the height is about 0.091m (3.6 in), and the straight and bent lengths of the compliant beam are about 0.229m (9 in) and 0.191m (7.5 in), respectively. The overall weight of the mobile sensing node is about 1 kg (2.2 lbs), most of which is contributed by the magnet wheels, motors, and batteries.

Hardware and Software Design

Fig. 2 illustrates the functional diagram of the flexonic mobile sensing node. A previously developed wireless sensing unit (consisting of sensor signal digitization, computational core, and wireless communication modules) is adopted for this work. Detailed description of the wireless sensing unit can be found in [13]. In this study, two such units (one for each 2-wheel car) are incorporated into the mobile sensing node, which communicate with each other through the wireless communication modules.

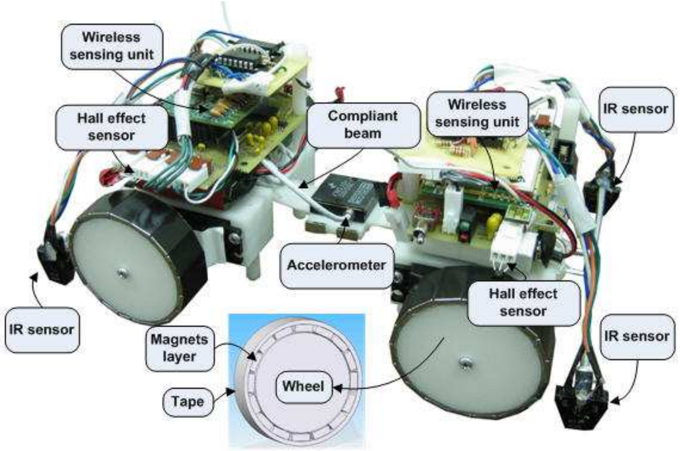


Fig. 1. Picture of a flexonic mobile sensing node

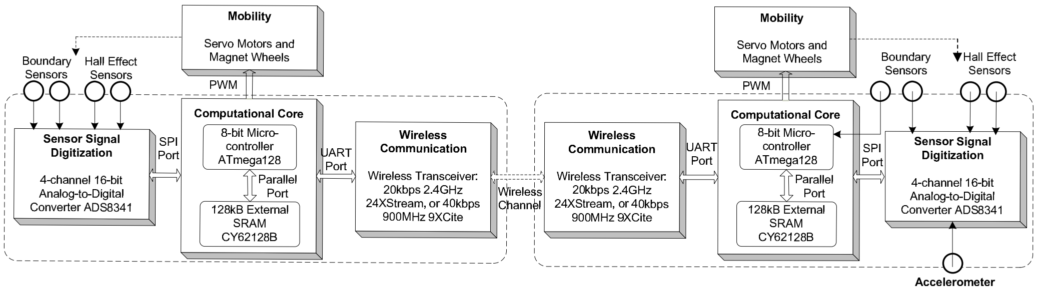
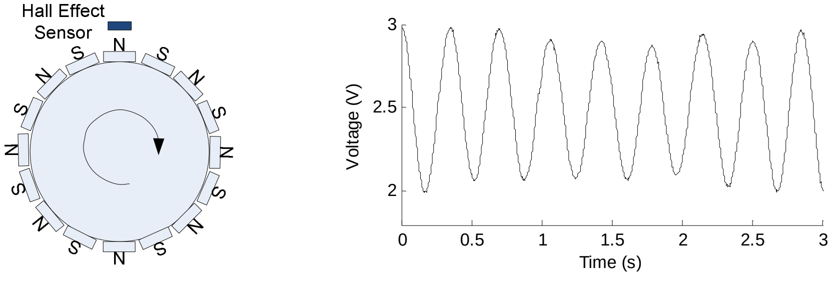


Fig. 2. Functional diagram of the flexonic mobile sensing node

As shown in Fig. 2, each ATmega128 microcontroller commands the servo motors with pulse-width-modulation (PWM) signals generated through the timer interrupt functions. The speed and direction of each motor are controlled by the duty cycle of the associated PWM signal. Since each wheel is actuated by an individual motor, it is necessary to adjust their angular velocities so that the wheels synchronize with each other as they rotate. Hall-effect sensors, which are capable of measuring the flux of a magnetic field, are placed upon the magnet wheels. Magnets with opposite polarities are alternatively placed around the wheel (Fig. 3(a)); thus, the magnet flux density measured by the Hall-effect sensor changes periodically as the wheel rotates. Fig. 3(b) depicts a typical measured voltage output of the sensor. Since in each period, two neighboring magnets pass underneath the Hall-effect sensor, the output signal from the Hall-effect sensor can be used to measure the angular velocity of the wheel.

In order to move the mobile sensing node (both forward and backward) safely on the underlying structural surface, IR sensors are placed at both sides of the front 2-wheel car as well as the rear 2-wheel car for surface boundary detection. In each IR sensor, an emitting diode emits infrared radiation, and a detection diode detects the radiation reflected from the structural surface. When the sensing node moves outside the surface boundary, changes can be captured from the reflected IR signal.

A feedback controller is designed for the flexonic mobile sensing node to stay synchronized and move safely, using data from the Hall-effect sensors and IR sensors at 200 Hz sampling frequency. Each 2-wheel car (front or rear) of the flexonic mobile sensing node is controlled by a single wireless sensing unit. Data from the IR sensors on the front 2-wheel car in the moving direction are required by both cars for boundary detection. Therefore, peer communication between the wireless sensing units on the two 2-wheel cars is needed for transmitting boundary information from the front 2-wheel car to the rear one. As the flexonic mobile sensor moves, both 2-



(a) (b)

Fig. 3. A Hall effect sensor measuring wheel rotation: (a) sensor fixed above a rotating magnet wheel; (b) the output of the Hall effect sensor as the magnet wheel rotates.

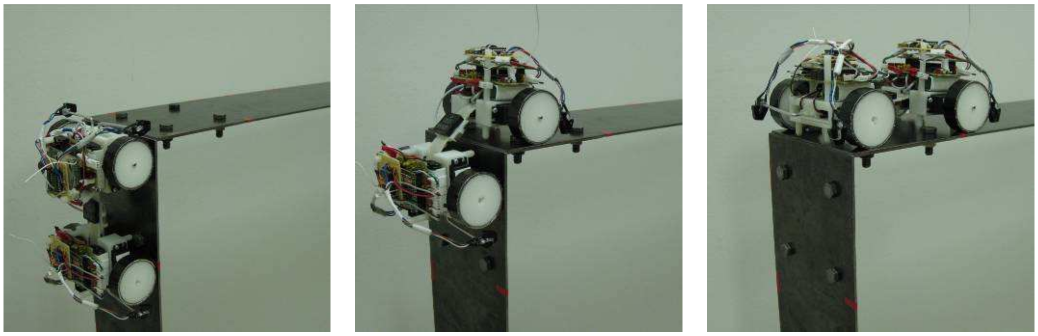
wheel cars synchronize the four wheels to a constant reference angular velocity. The synchronization is conducted based upon the difference between the reference angular velocity and the angular velocity measured by Hall-effect sensors. The control rate is set to 20 Hz. As the front 2-wheel car detects that one wheel (say left side) is moving out of boundary, it wirelessly communicates with the rear 2-wheel car. Consequently, the two wheels on the left side will be accelerated to immediately correct the mobile sensing node to stay inside the boundary of the structural surface.

LABORATORY EXPERIMENTS

A 2D laboratory steel portal frame structure is constructed for examining the concept feasibility and the performance of the flexonic mobile sensing nodes. The span of the portal frame is 1.524m (5 ft), and the height is 0.914m (3 ft) [11]. The beam and two columns have the same rectangular section area of 0.152m (6 in) × 0.003m (1/8 in). Hinge connections are adopted at the bases of the two columns.

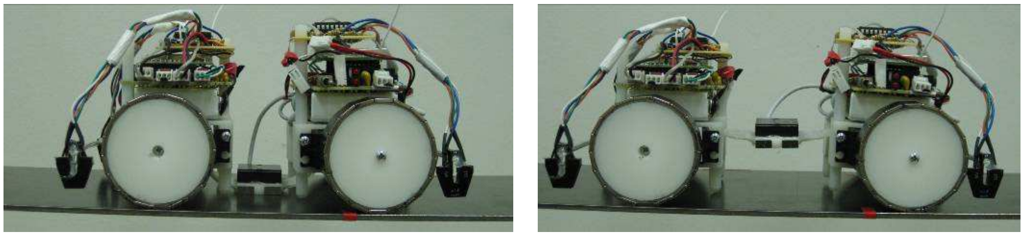
Fig. 4 shows the flexonic mobile sensing node able to transit from the left column to the beam. Fig. 5 shows the mobile sensor attaching/detaching the accelerometer on/from the structural surface. When a measurement is to be made, the two 2-wheel cars are driven towards each other to buckle the compliant beam downward to the surface. With the assistance of the magnets fixed on the compliant beam, the accelerometer is attached firmly on the steel surface as shown in Fig. 5(a). After measurement, the two 2-wheel cars move in opposite directions (straightening the beam) to lift the accelerometer away from the surface (as shown in Fig. 5(b)).

Experiments were conducted to compare data collected by the mobile sensing



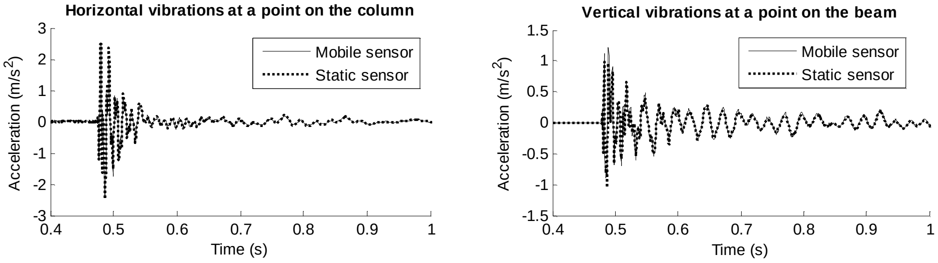
(a) (b) (c)

Fig. 4. A flexonic 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.



(a) (b)

Fig. 5. Side view of the flexonic magnet-wheeled mobile sensing node: (a) sensor attachment; (b) sensor detachment



(a) (b)

Fig. 6. Comparison between time history data measured by a mobile sensor and a static sensor: (a) both sensors mounted at a point on the left column; (b) both sensors mounted at a point on the beam

node and a static sensor. In these experiments, a static sensor is mounted at the same location on the structure as a mobile sensing node. Fig. 6(a) illustrates the comparison between mobile sensor data and static sensor data, when both sensors are mounted at a point on the left column, and an impact hammer is used to hit the left column. Fig. 6(b) illustrates a similar comparison where both the mobile sensor and a static sensor are mounted at a point on the beam, and the impact hammer is used to hit the same point on the left column. A sampling frequency of 2 kHz is used for the mobile and static sensor data collection. Fig. 6 shows that the mobile sensor data closely match the static sensor data and the difference can be neglected.

NUMERICAL SIMULATIONS FOR TRANSMISSIBILITY FUNCTION ANALYSIS

In order to detect potential damage on the steel frame structure, transmissibility function analysis will be adopted. Although experimental work will follow, initial investigation through numerical simulations is presented herein.

The equations of motion for a linear structure under external excitation can be formulated as:

$$\mathbf{M}\ddot{\mathbf{x}}(t)+\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{K}\mathbf{x}(t)=\mathbf{f}(t) \tag{1}$$

where $\mathbf{x}(t)$ is the n×1 displacement vector, $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ is the viscous damping matrix, $\mathbf{K}$ is the stiffness matrix, and $\mathbf{f}(t)$ is the external input vector. Using Fourier transform, the following frequency domain equation could be derived from Eq. (1):

$$\mathbf{X}(\omega)=\mathbf{H}(\omega)\mathbf{F}(\omega) \tag{2}$$

where $\mathbf{H}(\omega)=(\mathbf{K}-\omega^2\mathbf{M}+i\omega\mathbf{C})^{-1}$ is the $n\times n$ frequency response function matrix of the system. The acceleration vector in the frequency domain can be expressed as:

$$\mathbf{A}(\omega)=-\omega^2\mathbf{H}(\omega)\mathbf{F}(\omega) \tag{3}$$

The transmissibility function $T_{ij}(\omega)$ between the output i and reference-output j is defined as the ratio of two frequency responses $A_i(\omega)$ and $A_j(\omega)$. Let $\mathbf{h}(\omega)$ be a row of $\mathbf{H}(\omega)$, then

$$T_{ij}(\omega)=\frac{A_i(\omega)}{A_j(\omega)}=\frac{-\omega^2\mathbf{h}_i(\omega)\mathbf{F}(\omega)}{-\omega^2\mathbf{h}_j(\omega)\mathbf{F}(\omega)}=\frac{\mathbf{h}_i(\omega)\mathbf{F}(\omega)}{\mathbf{h}_j(\omega)\mathbf{F}(\omega)} \tag{4}$$

An integral damage indicator between the degree of freedom i and j is defined as

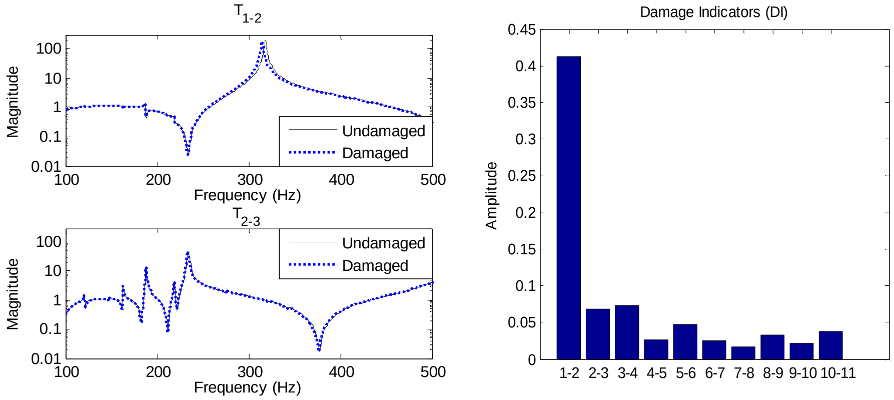
$$DI_{ij} = \int_0^\infty \left| T_{ij}^u - T_{ij}^d \right| d\omega \Big/ \int_0^\infty \left| T_{ij}^u \right| d\omega \tag{5}$$

where $|\bullet|$ denotes the magnitude; superscript u represents the undamaged structure and d represents the damaged structure.

A 2D finite-element (FE) model for the laboratory steel portal frame is built in ANSYS for numerical simulations. In the FE model, each column is divided into 72 elements, and 4 acceleration measurement locations (A1 to A4) are allocated on the left column (Fig. 7). The beam is divided into 120 elements, and 7 acceleration measurement locations (A5 to A11) are uniformly allocated on the beam. Structural damage is simulated as 35% stiffness reduction to two continuous elements at the left column, 0.229m (9in) above the hinged joint. A constant damping ratio of 0.003 is used for all modal frequencies. The damping ratio is determined based upon the comparison between simulated and experimental data.

In the simulation, hammer impact is applied horizontally at the left column, 0.229m (9in) below the upper left rigid joint. To simulate the effect of a plastic hammer tip, the time duration of the impact force is set as 1ms, and the peak amplitude is about 30N. Sampling frequency for acceleration data collection is 2kHz. Using the acceleration response computed by ANSYS, transmissibility functions and damage indicators (DI) are calculated using MATLAB. Fig. 8(a) illustrates that the stiffness reduction causes a peak shift (around 320Hz) to the transmissibility function between A1 and A2. Meanwhile, no obvious change is caused to other transmissibility functions (e.g. $T_{2\text{-}3}$ shown in Fig. 8(a)). Fig. 8(b) shows that the largest damage indicator is determined as $DI_{1\text{-}2}$, which demonstrates the correct damage location.

Fig. 7. Schematics of the steel portal frame



(a) (b)

Fig. 8. Simulation results for damage between accelerometers A1 and A2 (100-500Hz): (a) Transmissibility Functions; (b) Damage Indicators.

SUMMARY AND DISCUSSION

Exploratory work harnessing mobile sensor networks for SHM is presented in this paper. The flexonic mobile sensing node described herein can reliably maneuver upon the laboratory steel portal frame. The mobile node also has the ability to attach/detach an accelerometer on/from structure surface. Preliminary experiments demonstrate that acceleration data collected by the flexonic mobile sensing node matches well with the static sensor data. Numerical simulations illustrate the effectiveness of transmissibility function analysis in identifying and locating damage on the structure. Future work will utilize acceleration data collected by the flexonic mobile sensing nodes for transmissibility function analysis. In addition, significant amount of efforts will be needed to make the flexonic mobile sensor nodes capable of navigating on a real-world structure built with ferromagnetic materials.

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