A Flexure-Based Mobile Sensing Node for the Health Monitoring of Steel Structures

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Abstract: In order to reduce the system cost and enhance the efficiency, a flexure-based mobile sensing node is developed for structural health monitoring (SHM). The mobile sensing node is a miniature robot that carries sensors and automatically navigates on a structure. In contrast to traditional robot design with rigid bodies, a compliant design is adopted for the mobile sensing node. The flexure-based compliance mechanism helps the mobile sensing node navigate on steel structures, and accurately measure structural vibrations. The performance of the mobile sensing node has been validated through laboratory experiments. Transmissibility function analysis is adopted for identifying structural damage using data collected by the mobile sensing nodes.

1. Introduction: As civil structures are continuously subjected to various adverse operational and environmental conditions, their safety conditions may deteriorate quickly. In the United States, more than one fourth of the bridges are categorized as structurally deficient or functionally obsolete [1]. It is estimated that a \$17 billion annual investment is needed for improving current bridge conditions; however, only \$10.5 billion is available every year. Therefore, there is a need to develop highly efficient structural health monitoring (SHM) systems for accurately determining structural conditions, so that the limit resources can be prioritized for structures with the most urgent need.

In recent years, wireless sensing technology has been widely explored for SHM, because the technology can significantly reduce the monetary and time cost for installing lengthy cables [2]. It is expected that as a transformative change to wireless sensing, the next revolution in sensor networks will be mobile sensing systems [3]. Some inspection robots have been developed by incorporating mobility with traditional sensors 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 [4]. Α beam-crawler has been developed for wirelessly powering and interrogating peak-strain sensors; the crawler moves along the flange of an I-beam by wheels [5]. In order to inspect the inner casing of ferromagnetic pipes, a compact robot with two magnetic wheels in a motorbike arrangement has been developed; the robot can slightly lift off the wheel in order to negotiate concave edges [6]. Although individual robots have been developed for various inspections, mobile sensor networks with dynamic reconfiguration have rarely been explored by researchers for SHM purpose.

Our previous research explored the concept of a flexure-based mobile sensing nodes [7-9]. The mobile sensing node is capable of attaching/detaching an accelerometer onto/from a steel structural surface. Meanwhile, this flexure-based mobile sensing node has the ability to negotiate on complex steel structures with narrow sections and highly abrupt angle changes. This paper summarizes the mechanical design of the mobile sensing node, as well as the application of a two-node mobile sensor network for structural damage detection. To exploit the dynamic reconfiguration provided by the mobile sensor network, a transmissibility-function -based damage detection approach is proposed to utilize the decentralized and localized vibration data. The rest of this paper begins with the mechanical design of the flexure-based mobile sensing node. Laboratory damage detection experiments with the two-node mobile sensor The network are then presented. transmissibility-function-based damage detection algorithm is introduced, and structural damage detection results are presented. Finally, the paper summarizes this research and proposes future work.

Design of the Flexure-Based Mobile Sensing 2. Node: Figure 1 shows a picture of the flexure-based mobile sensing node developed by Lee et al. [7]. This mobile sensing node consists of three substructures: two 2-wheel cars and a compliant connection beam. Each 2-wheel car contains a body frame, two motorized wheels, batteries, a wireless sensing unit [10], as well as associated sensors. The compliant connection beam is made of spring steel. An accelerometer (manufactured by Silicon Designs, Inc.) is mounted at the middle of the compliant beam between the 2-wheel cars. One wireless sensing unit is responsible for collecting and processing data from the accelerometer. The width of the mobile sensing node is 0.152m (6 in), the height is 0.091m (3.6 in), and the length is 0.229m (9 in). 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.

2.1 Negotiation on Steel Structure: As shown in Figure 1, the wheels of the mobile sensing node are surrounded by thin magnets for providing enough attraction forces to climb on ferromagnetic structures. Hall-effect sensors, which are capable of measuring the flux of a magnetic field, are fixed above the magnet wheels. As the wheel rotates, the north and south poles of the small magnets sequentially pass underneath the Hall-effect sensor. Therefore, the magnetic flux density measured by the Hall-effect sensor changes periodically, and the angular velocity of the wheel can be derived and then controlled in real time. In order to move the mobile sensing node (both forward and backward) safely on the underlying structural surface, infrared (IR) sensors are placed at both left and right sides of the front and rear 2-wheel cars for surface boundary detection. When an IR sensor moves outside the surface boundary, changes can be captured from the strength of the reflected IR signal, so that the movement



Figure 1. Picture of the flexure-based mobile sensing node

direction can be immediately corrected. Real-time feedback control of the motors is performed by the wireless sensing units.

Compared with a traditional robot design where the distance between the axles of the front and rear cars is fixed, the compliant connection beam can offer significant advantage for corner negotiation. This is illustrated by the kinematic analysis of the direct-line axial distance during corner negotiation. With r denoting the wheel radius, Figure 2(a) shows the initial side view before the mobile node moves over a corner. Case 1 describes a concave corer, and Case 2 describes a convex corner. In both cases, the initial axial distance is 3r (i.e. s_0 , the length of the compliant connection beam), and the front car is set as 7r away from the corner. It is assumed that the front and rear axles move at the same constant speed and there is no slippage between each wheel and the flat structural surface. The non-slipping assumption is valid given the strong magnetic attraction force and the large friction coefficient between the wheels (wrapped with frictional tape) and the structural surface. With the above assumptions, the direct-line distance between the two axles changes when the mobile node moves over a



Figure 2. Kinematic simulation for the direct-line distance *s* between front and rear axles while negotiating a concave/convex corner ($s_0 = 3r$)

corner (either concave or convex). For each case, Figure 2(b) plots the direct-line axial distance s against the front axle displacement along the structural surface, where all quantities are normalized by the wheel radius r. When the mobile sensing node negotiates both corners, the axial distance s reduces, which is easily accommodated by the compliant connection beam. This also suggests that if a rigid connection beam is used, constant speeds for both wheels cannot be maintained and slippage will occur, which may increase tear and wear to the driving system.

To investigate the effect of the beam length, Figure 3 plots the kinematic simulation results for the direct-line axial distance during convex corner negotiation with different beam lengths (i.e. initial axial distance s_0). The beam length varies from 3r up to 5.43r. The largest value, 5.43r, is the same as the current prototype implementation, where the wheel radius is 25.4cm (1 inch) and the beam length is 13.8cm (5.43 inch). It is observed that during the movement, longer beam length resulted in larger shortening to the direct-line axial distance s, although the shortening is accommodated by the compliant conveniently mechanism. To validate the simulation result, laboratory experiments are conducted for convex corner negotiation at constant wheel speed (Figure 4). During the movement, the traces of the wheels are captured by image processing techniques and marked in the Figure 4. The distance history between the front and rear axles is then extracted from the traces, which shows a minimal value of s/r = 4.2 during the movement. This is very close to the simulation result 4.15 (as shown by the $s_0 = 5.43r$ case in Figure 3).

2.2 Accelerometer Attachment: The other feature of



Figure 3. Kinematic simulation for the direct-line distance *s* between two axles during convex corner negotiation (with various lengths of compliant connection beam).



Figure 4. Corner negotiation in the laboratory experiment.

the mobile sensing node is the ability to offer accurate acceleration measurement by firmly attaching the accelerometer onto the structural surface. The attaching procedure is achieved by commanding the two cars to move towards each other to bend the center of compliant beam towards the structural surface. In addition, small-size magnet pieces are arranged around the center of the beam to firmly attach the accelerometer on the steel structural surface. After measurement, the two cars move in opposite directions to straighten the beam and lift the accelerometer away from the steel surface. After the accelerometer is lifted, the mobile sensing node resumes its mobility and moves to next location for another measurement.

As shown in Figures $5(a) \sim 5(c)$, the accelerometer can be attached in different directions (e.g. downward, upward, or horizontal) towards the structural surface. Taking the rear car as the fixed end reference, the front car can be modeled as a slider connected through the compliant beam (Figure 5(d)). During laboratory experiments for sensor attachment, the traces of the wheels are captured by image processing techniques and marked in Figures $5(a) \sim 5(c)$. The distance change between the front and rear axles, u_1 , and the displacement of the accelerometer towards the structural surface, w_s , can be extracted from the figures and normalized by the beam length L. Figure 5(d)shows that the relationship between u_1 and w_s approximately follows the same curve for different attaching directions (with respect to the gravity). This consistent relationship may have resulted from the relatively light weight of the accelerometer (about 50 grams) and the compliant beam made of thin spring steel. In this prototype design, Hall-effect sensors measure the wheel rotation, from which relative movement u_1 can be derived. The result is then used in real-time motor control for moving the accelerometer by certain distance w_s towards the structure surface.



Figure 5. Sensor attachment: (a) above a horizontal beam; (b) under a horizontal beam; (c) on a vertical column; (d) relationship between w_s and u_1 (normalized by the beam length *L*).

3. Laboratory Experiments: Laboratory experiments are conducted to validate the performance of the mobile sensing nodes for SHM. This section first discusses the laboratory experimental setup and then introduces transmissibility function analysis. Three damage scenarios and corresponding damage detection results using transmissibility function analysis are presented: the first scenario simulated with an extra mass block, the second scenario simulated with loosened bolts, and the third scenario simulated with loss of section area.

3.1 Experimental Setup: A laboratory steel portal frame is constructed (Figure 6). The span of the portal frame is 1.524m (5 ft), and the height is 0.914m (3 ft). The beam and two columns have the same rectangular section area of 0.152m (6 in) $\times 0.005m$ (3/16 in). Hinge connection is adopted at the base of each column. Each column is connected with the beam through a bolted angle plate, with 4 bolts on the beam and 4 bolts on the





Figure 6. The laboratory steel portal frame for damage detection using mobile sensing nodes: (a) picture of the portal frame with mobile sensing nodes at A1 and A2; (b) schematic of experimental setup.

column. The torque of every bolt is initially set at 13.56Nm (120 lbs-in) for the undamaged structure.

As shown in Figure 6(b), two mobile sensing nodes are used to sequentially take measurements at every pair of locations (A1-A2, A2-A3,..., A10-A11). In the experiments, when the two mobile sensing nodes arrive at one pair of measurement locations, the accelerometers carried by both mobile nodes are attached onto the structural surface. A hammer impact is then applied at the middle of these two adjacent measurement locations. Impact responses at these two locations are then recorded by the mobile sensing nodes. The mobile sensing nodes can either transmit measurement data to the server, or conduct on-board analysis. Then the two mobile sensing nodes detach accelerometers from the structural surface, and move to the next pair of measurement locations. The sampling rate for acceleration measurement is set to 2,500 Hz. In order to reduce the effect of experimental uncertainties, measurement at each location pair is repeatedly taken for 20 times.

3.2 Transmissibility Function Analysis: Many vibration-based algorithms have been developed for structural damage detection[11]. Among these algorithms, transmissibility function analysis has attracted considerable attention, because of its

effectiveness in identifying damage using output data only [12-15].

If external excitation is only applied at the *k*-th degree of freedom (DOF), the transmissibility function $T_{ij}(\omega)$ between the DOF *i* and reference-DOF *j* is defined as the ratio between the frequency spectra of the acceleration at DOF *i* and DOF *j*, $A_i(\omega)$ and $A_j(\omega)$:

$$T_{ij}(\omega) = \frac{A_i(\omega)}{A_i(\omega)} \tag{1}$$

It can be derived that for single excitation (at the *k*-th DOF), the transmissibility function can be further simplified as the ratio between two entries of the frequency response function (FRF) matrix, $H_{ik}(\omega)$ and $H_{ik}(\omega)$:

$$T_{ij}(\omega) = \frac{H_{ik}(\omega)}{H_{ik}(\omega)}$$
(2)

Eq.(2) shows that the transmissibility function corresponds to inherent dynamics properties of the structure. In addition, Eq.(1) shows that during experiments, the determination of transmissibility functions does not require measuring the excitation force.

In order to reduce the effect of experimental uncertainties, the vibration experiments are repeated for N times (N=20 in this study). Then the average transmissibility function \tilde{T}_{ij} is calculated:

$$\tilde{T}_{ij} = \frac{1}{N} \sum_{l=1}^{N} (T_{ij})_l$$
(3)

where $(T_{ij})_l$ represents the transmissibility function T_{ij} calculated from the *l*-th repeated test at DOFs *i* and *j*.

The damage indicator (DI) between DOFs *i* and *j* is defined as following:

$$DI_{ij} = \int_{\omega_1}^{\omega_2} \frac{\left|\ln\left|\tilde{T}_{ij}^{U}\right| - \ln\left|\tilde{T}_{ij}^{D}\right|\right|}{\left|\ln\left|\tilde{T}_{ij}^{U}\right|\right|} d\omega$$
(4)

where ω_1 and ω_2 are the lower and upper boundaries of the interested frequency span; \tilde{T}_{ij}^U represents the average transmissibility function of the undamaged structure; \tilde{T}_{ij}^D represents the average transmissibility function of the damaged structure; "ln" means natural logarithm. In this experimental study, ω_1 and ω_2 are set to 100 Hz and 1,000 Hz, respectively.

Furthermore, repeatability check is performed to ensure that experimental uncertainties, including sensor noise and the application of external input, have negligible influence to the damage detection results. Taking the undamaged structure as an example, the Ndata sets are divided into two groups according to the sequence number. Data sets with odd sequence numbers form one group, and data sets with even sequence numbers form the other group. Then the average transmissibility functions of these two groups are calculated by

$$T_{ij}^{U_{-}odd} = \frac{2}{N} \sum_{l=1}^{N/2} (T_{ij}^{U})_{2l-1}$$
(5)

$$T_{ij}^{U_{-}even} = \frac{2}{N} \sum_{l=1}^{N/2} (T_{ij}^{U})_{2l}$$
(6)

The repeatability indicator for the undamaged structure is then defined in a similar approach to the damage indicator:

$$RI_{ij}^{U} = \int_{\omega_{i}}^{\omega_{2}} \frac{\left|\ln\left|T_{ij}^{U}\right|^{-odd} - \ln\left|T_{ij}^{U}\right|^{-even}\right|}{\left|\ln\left|T_{ij}^{U}\right|^{-odd}\right|} d\omega$$
(7)

Similarly, the repeatability indicator RI_{ij}^{D} for the damaged structure can be obtained using the *N* data sets collected from a damaged structure. Note that a smaller repeatability indicator *RI* represents a higher level of repeatability.

3.3 Damage Scenario I – Extra Mass Block: In Damage Scenario I, a steel mass block of 0.575 kg (1.27 lbs) is bonded at the left column between location A1 and A2 for simulating a reversible damage, as shown in Figure 7. In contrast, the mass of the left column is 4.985 kg (10.99 lbs). Same as the measurement scheme for the undamaged structure, the two mobile sensing nodes take measurement at every pair of locations (A1-A2, A2-A3,..., A10-A11) in sequence, and measurement at each location pair is repeatedly taken for 20 times.

With all the experimental data sets, the average transmissibility functions for both the undamaged and damaged structures are computed for all location pairs (i = 1, ..., 10 and j = i + 1) using Eqs.(1) and (3). The damage indicators (*DI*) are then obtained by Eq. (4), and shown in Figure 8. For each location pair, the largest damage indicator is $DI_{1-2} = 0.73$, which agrees with the correct damage location. Repeatability



Figure 7. Damage Scenario I - an extra mass block mounted between locations A1 and A2 shown in Figure 6.



Figure 8. Damage Scenario I – the damage indicators and repeatability indicators

indicators for both the undamaged and damaged structures are also shown in Figure 8. The repeatability indicators are much smaller than the damage indicators, which demonstrates that the damage detection experiments are repeatable, and experimental uncertainties have limited effects to the damage localization results.

3.4 Damage Scenario II – Loosened Bolts: In Damage Scenario II, four bolts at the upper left corner of the structure, which connect the beam and the angle plate, are loosened (Figure 9). The torque of each of the four bolts is reduced from 13.56Nm (120 lbs-in) to 0.565Nm (5lbs-in). The two mobile sensing nodes again take measurement at every pair of locations (A1-A2, A2-A3,..., A10-A11) in sequence. Measurement at each location pair is also repeatedly taken for 20 times.



Figure 9. Damage Scenario II – Four bolts are loosened between locations A3 and A4 shown in Figure 6.



Figure 10. Damage Scenario II – the damage indicators and repeatability indicators

The damage indicators and repeatability indicators for Damage Scenario II are shown in Figure 10. The largest damage indicator is $DI_{3.4} = 0.56$, which again agrees with the correct damage location. The small repeatability indicators shown in Figure 10 demonstrate that experimental uncertainties have limited effects to the damage localization results.

3.4 Damage Scenario III – Loss of Section Area: In Damage Scenario III, reduction in section area is introduced to the left column (Figure 11). The width of the section loss is 0.006 m (0.25 in), and the total length of the loss is 0.0075 + 0.0075 = 0.015 m (0.6 in), about one tenth of the column width. The location of the section loss is at 0.533 m (21 in) above the column base, which is between locations A2 and A3. The two mobile sensing nodes again take measurement at every pair of locations (A1-A2, A2-A3,..., A10-A11) in sequence, and measurement at each location pair is repeatedly taken for 20 times.



Figure 11. Damage Scenario III – loss in section area is introduced to the left column between locations A2 and A3 shown in Figure 6.



Figure 12. Damage Scenario III – the damage indicators and repeatability indicators

The damage indicators and repeatability indicators for Damage Scenario III are shown in Figure 12. The largest damage indicator is $DI_{2-3} = 0.49$, which also agrees with the correct damage location. The small repeatability indicators shown in Figure 12 again demonstrate that experimental uncertainties have limited effects to damage detection.

4. Conclusion: This study investigates flexure-based mobile sensing nodes and their application for SHM. The mobile sensing node developed in this research is of negotiating on steel capable structures, attaching/detaching an accelerometer on/from a structural surface, taking measurement and transmitting the measurement to a central server. Kinematic analysis illustrates the advantage in mobility provided by the compliant mechanism. Laboratory experiments are carried out to validate the performance of a two-node mobile sensor network for structural damage detection. Transmissibility function analysis is applied on the acceleration data collected by the mobile sensing nodes. Damage locations are successfully determined for all three damage scenarios.

Future research will be devoted in improving the mobile sensing nodes for navigating on real-world structures built with ferromagnetic materials. Besides, a mobile excitation node can be developed for applying small-magnitude impact forces to one local area of a structure.

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