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Nathan Sharp, Alan Kuntz, Cole Brubaker, Stephanie Amos, Wei Gao, Gautam Gupta, Aditya Mohite, Charles Farrar, David Mascareñas, "An asynchronous sensor skin for structural health monitoring applications," Proc. SPIE 9061, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2014, 90611R (10 April 2014); doi: 10.1117/12.2045093

SPIE.

Event: SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, 2014, San Diego, California, United States

An Asynchronous Sensor Skin For Structural Health Monitoring Applications

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ABSTRACT

In crack detection applications large sensor arrays are needed to be able to detect and locate cracks in structures. This paper analyzes different sensor shapes and layouts to determine the layout which provides the optimal performance. A “snaked hexagon” layout is proposed as the optimal sensor layout when both crack detection and crack location parameters are considered.

In previous work we have developed a crack detection circuit which reduces the number of channels of the system by placing several sensors onto a common bus line. This helps reduce data and power consumption requirements but reduces the robustness of the system by creating the possibility of losing sensing in several sensors by a single broken wire. In this paper, sensor bus configurations are analyzed to increase the robustness of the bused sensor system. Results show that spacing sensors in the same bus out as much as possible increases the robustness of the system and that at least 3 buses are needed to prevent large segments of a structure from losing sensing in the event of a bus failure.

Keywords: Asynchronous, Structural health monitoring

1. INTRODUCTION

In many structural health monitoring (SHM) applications, the monitoring system is looking for cracks in the structure which is indicative of damage. In some cases exciting and/or monitoring with vibro-acoustic or thermal signals can be an effective method for monitoring cracks. In many situations, however, especially where the system is remote and weight, size, and power consumption are limited (e.g. Unmanned Aerial Systems, UAS), these traditional SHM strategies are not as effective.

A number of crack monitoring systems are currently being explored by researchers. Distributed fiber optic systems have been developed to detect cracks as well as measure temperature and strain in multiple locations^{1,2,3,4,5}. The distributed sensors are suitable for large structural applications, which is important in crack detection. However, these systems have not found widespread usage due to insufficient resolutions, weak detectable signals, and cumbersome demodulation systems⁶. Another strategy is to use tomography to estimate the conductivity which can detect cracks since a crack will cause a loss of conductivity^{7,8}. The advantage of this strategy is that the entire area within the tomography boundary has sensing capability. The disadvantages of this strategy is that estimating conductivity from boundary values is an inverse problem and inverse problems have inherent limitations in size and resolution⁹. Elastomeric capacitive sensing skins have also recently been developed¹⁰ and hold promise for health monitoring of civil infrastructure. A fourth strategy for crack detection is to embed or print wires on a structure and monitor for loss of connection, which would indicate a crack¹¹. The advantages of this system are that it is the least expensive option and can easily be scaled to almost any size. One disadvantage of this method is that, unlike fiber optic systems, there is no way to know where a wire has been cut. Another disadvantage is that, unlike the tomography method, the entire area does not have sensing capability (a crack must go through a wire). These disadvantages can be minimized by choosing smart sensor shapes and layouts. However, to the best of our knowledge no one has analyzed how the sensor shape and layout affects its crack detection and crack location performance. Since sensing skin systems would likely be most effective in cases where maintenance and resources are limited, it is important that sensors are created and arranged in such a way as to maximize information and robustness. This paper will analyze effects of sensor shape and layout in the wire-based sensor skins only.

4. SENSOR LAYOUT ANALYSIS

In this section we are primarily concerned with the design and layout of capacitive/resistive sensors that can be used to detect cracks. The sensors considered here consist of a curvilinear profile that experiences a change in either capacitance/resistance when it is cut through. This change in capacitance/resistance is used to indicate the presence of damage in that sensor. The curvilinear nature of these sensors allows for a sensor layout pattern that consists of any combination of curvilinear elements. It is clear that some layout patterns will have superior properties for detecting cracks than others, and finding high-performance crack detection patterns is the primary focus of this section. Zhang et al.¹¹ proposed a grid patterned crack detection sensor layout shown in Figure 1. In this figure, the solid lines represent conductive paths on the front side of the resin paper substrate and the dashed lines represent conductive paths on the back side. Throughout the paper this convention will be used to represent lines which intersect but do not touch. While this layout was shown to be able to detect and locate cracks, no analysis was done to determine how this sensor layout performs compared to other layouts. In order to do this analysis, fitness metrics must be outlined so that performance can be compared quantitatively. The most obvious performance metric of a crack detection sensor is how well it detects cracks. Therefore, one goal of the sensor layout and shape design is to minimize the crack length at which a crack is detected. Another important job of the sensor (at least in some applications) is locating the crack. Therefore, the other goal of the sensor layout and shape design is to minimize the area of the crack location uncertainty when a crack is detected. A third goal is to minimize the number of sensors needed to achieve the first two goals.

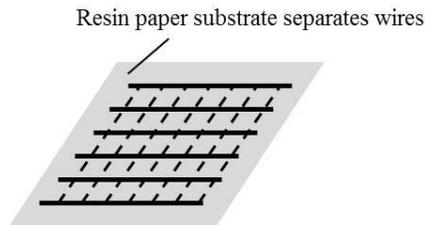


Figure 1: Previously proposed grid layout.

The first step in analyzing sensor performance is to find appropriate bounding cases. One way to get very good crack detection performance with very few sensors is to take the grid pattern and connect all the vertical lines together and all the horizontal lines together, as shown in figure 2. This will be referred to as the “snake” pattern for convenience sake. The detection performance of this pattern is only limited by how closely neighboring lines are spaced together and only uses 2 sensors no matter how large the sensor area. The downside of this pattern is that there is no crack location information. The other bounding case is a layout with the smallest possible location uncertainty with a fixed number of sensors per unit area. To find this, a layout that can has sensors that tile and pack together tightly is needed. Both squares and hexagons (where the sensor would be the boundary of the square/hexagon) pack together perfectly and therefore offer the same location uncertainty performance, but our analysis showed hexagons offer slightly better crack detection performance so a hexagonal layout was used.

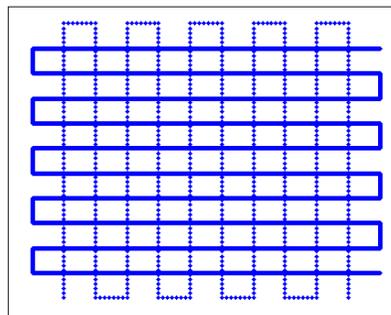


Figure 2: "Snake" sensor layout.

Figure 3 shows the crack detection performance and location performance for the three sensor layouts described above. The horizontal axis shows the average crack length at detection, while the vertical axis shows the area of the location uncertainty of the crack at detection. The area of location uncertainty is defined as the area of the surface where the crack could possibly be located. Figure 4 shows an example of the area of location uncertainty in a grid pattern with a detected crack. An ideal sensor would be at the origin. A surface with an area of 1 m² was populated with sensors of the three different layouts shown in Figure 3. For this simulation only two dimensions were considered: all cracks were treated as penetrating the surface completely. This assumption would be realistic for very thin structures or structures where only a surface needs to be monitored (perhaps a composite laminate), but would not be accurate in bulk structures where depth also needs to be considered. It would also be valid in the case of a tear in an intelligent tamper-indicating seal. To be conservative the thickness of the cracks has been neglected. A Monte Carlo analysis was performed by simulating 5000 through-thickness cracks in random locations and the cracks were propagated linearly in a random direction until the crack touched a sensor. The locations of the cracks were uniformly distributed over a circular area in the center of the simulated plate. The radius of the circle is such that it covers one complete hexagonal sensor, and half of the width of the adjacent sensors. Figure 5 shows a representative example of the simulation area for a hex-style sensor. In this case the sensors consist of two nested hex profiles. The results for this particular sensor configuration are not reported in this paper, but we use this example because it most clearly shows the nature of how the simulation was carried out. The direction of propagation of the cracks was also uniformly distributed from 0 to 360 degrees. The cracks were propagated linearly until they crossed a sensor outline. Upon crossing a sensor outline we decide the sensor has been detected and stop that simulation. The average length before a crack crosses a sensor is displayed along the horizontal axis of Figure 3. In order to show how the values are a function of the number of sensors per unit area, the crack simulation was run with 6, 8, 10, 12, 14, 16, and 18 sensors covering the 1 m² area (except for the snake layout since it always has 2 sensors by definition). More sensors for the same area implies lower average crack length and lower area uncertainty, so the lower left values represent the highest number of sensors. Therefore, from lower left to upper right respectively, each value can be compared directly. This plot shows that, as expected, the snake pattern performs best at crack detection but worst at locating the crack, the hexagonal pattern performs best at locating the crack but worst at detecting it, and the grid pattern is in between for both.

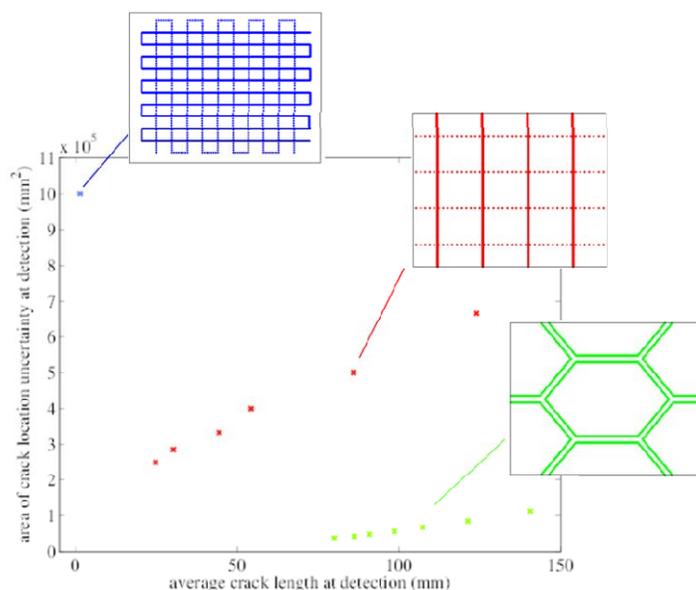


Figure 3: Performance plot of three different sensor layouts.

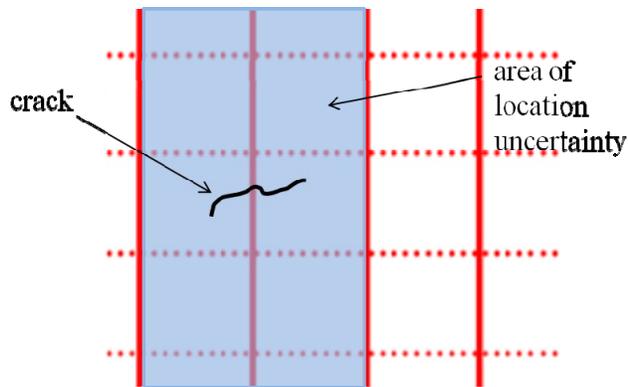


Figure 4: Area of location uncertainty example

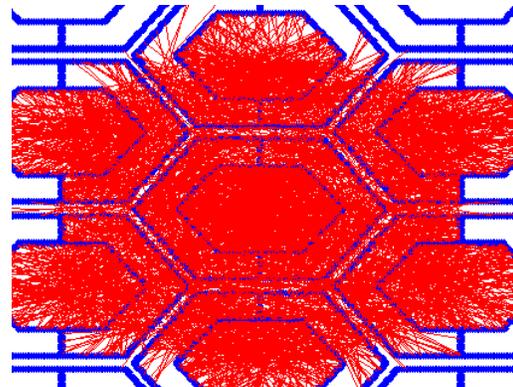


Figure 5: Example of the simulation area for determining sensed crack lengths. In this image a sensor consisting of two nested hex profiles is shown to give some sense of how cracks were allowed to propagate.

The advantages of the snake pattern and the hexagonal pattern can be combined to get the advantage of each layout by patterning “snaked” sensors in a hexagonal shape, as shown in Figure 6. Figure 7 shows the performance plot shown in Figure 3 but also includes the snaked hex layout included (note that plots showing layout shapes are not to scale relative to each other). This layout has the same area uncertainty as the hexagonal pattern and crack detection performance which is almost as good as the snake pattern. Therefore, this plot shows that the snake layout is the best if crack location information is not important and the snaked patterned shape layout is best if location information is important. Note that, unlike the grid and hexagon layouts, the crack detection performance of the snaked hexagon layout is not very dependent on the number of sensors. Instead it is dependent on the spacing of the snaked lines. The crack detection performance for both the snake pattern and snaked hexagon layouts could be better or worse than that reported in Figure 3 depending on what spacing is used. In this simulation, a spacing of 2 mm was used between lines for both sensor layouts. The constraints that would determine the best spacing would be cost (smaller spacing means more conductor/manufacturing time for laser reduction), the thickness of the conductor, and the length of the conductor before the normal resistance gets too high. Also note that the crack detection performance of the grid pattern would eventually converge to that of the snake pattern if enough sensors were used, but the same performance parameters can be gained using fewer sensors with the snaked hexagon layout.

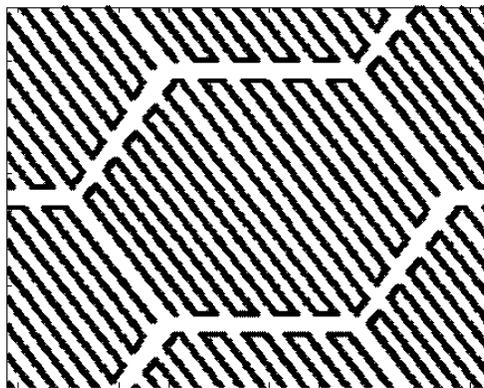


Figure 6: "Snaked hexagon" layout.

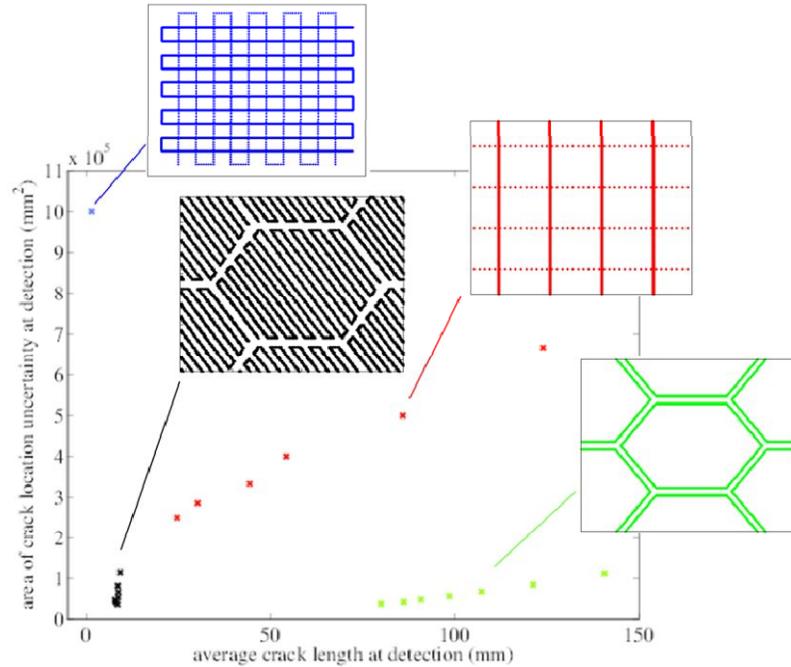


Figure 7: Performance plot with snaked hexagon layout.

5. BUS CONFIGURATION ANALYSIS

In previous work we have developed a crack detection system which reduces the number of required, unique communication channels by placing several sensors onto a common bus line. The bus would work by multiplexing the sensors, similar to work which has been done previously^{14,15}. In this case the simplest way to bus the sensors together would be the use of time division multiplexing, where only one of the sensors on each bus is being sensed at any given time and the sensor which is being sensed rotates through all of the sensors on the bus. This helps reduce wiring, number of analog-to-digital converters, bandwidth, and power consumption requirements. Unfortunately this comes at the expense of reducing the robustness of the system by creating the possibility of losing communication with several sensors in the event a bus wire breaks. It is preferable to develop new sensor layouts that degrade gracefully as the individual components of the system fail, but instead to decrease the performance of the system over the entire structure. We now consider how to design sensor/bus layouts that are robust against single points of failure. This study is predominantly concerned with the robustness properties of the network one level of abstraction up from the individual sensor performance with respect to layout type considered in the previous section. Based on the results above, a hexagonal pattern was selected to be tested as the sensor type being connected using 2, 3, 4, 6, 8, and 12 unique buses. Since the goal was to prevent allowing a single bus failure to create a region incapable of being observed by the sensors, the sensors were spaced as far apart from each other as possible. For the purposes of the research in this section each hexagon can be thought of as a sensor that is capable of detecting the presence of a crack within its boundaries. Figure 8 shows the sensor arrangements with 2, 3, and 4 sensors, where hexagons of like colors are connected on the same bus.

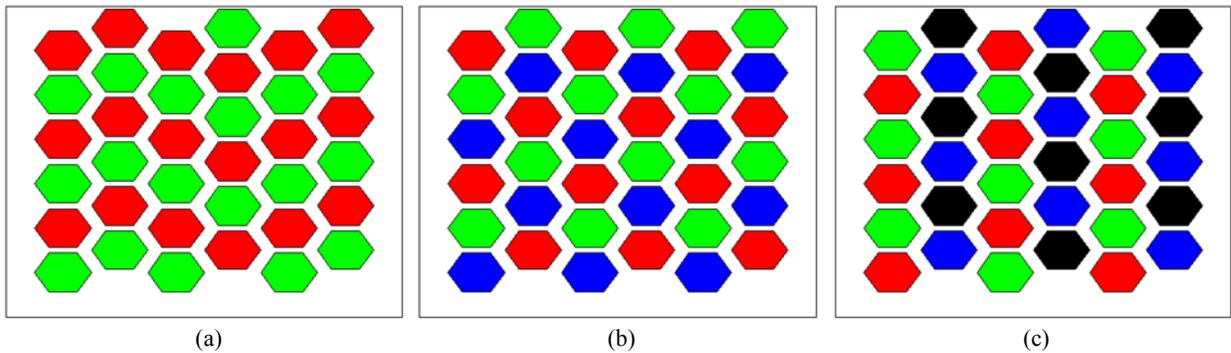


Figure 8: Sensor configurations for (a) 2, (b) 3, and (c) 4 buses.

The performance of each sensor configuration was tested in the event of a single bus failure. After removing all of the sensors from one of the buses in each case, 10,000 cracks were randomly populated on a sensor skin surface using a uniform distribution on a circle centered in the middle of the simulation area. The cracks were advanced in a random direction (uniformly distributed over 0-360 degrees) until a crack hit a sensor. In order to simplify the simulation the entire hexagon of each active sensor was considered sensitive to a crack. This simulation was run 10 times for each ordered sensor layout as well as 10 times for a random sensor layout with the same number of broken sensors. The sensor grid was 10 rows and columns, and the simulated cracks were generated a distance away from the edges to prevent edges from skewing the results. Figure 9 shows the sensor layout with 3 buses where one of the buses has been removed for (a) the random case and (b) the ordered case.

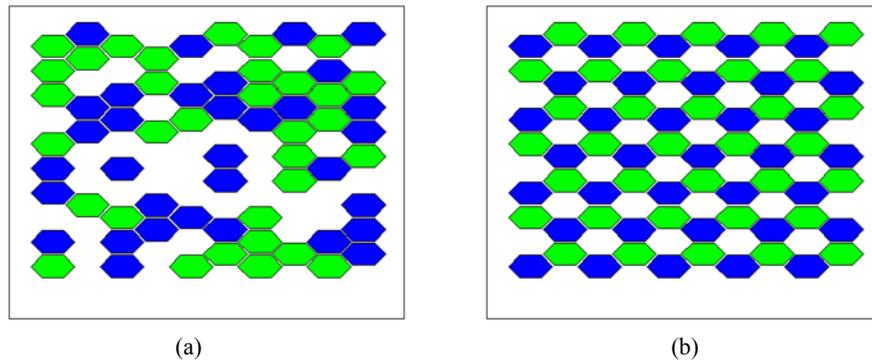


Figure 9: 3 bus sensor configuration for (a) random and (b) ordered cases. In this plot one of the three buses has been rendered inoperable and thus is simply whited out leaving only the two remaining buses.

Boxplot results for the simulations are shown in Figure 10. The labels for each boxplot state the number of buses for the simulated case followed by “R” for random or “O” for ordered. The “NB” label stands for “not broken”, or a fully functional sensing skin. Figure 11 shows the results of each case when all of the crack lengths are averaged to get a single average value. Unsurprisingly, the ordered layouts perform significantly better than the random layouts. The results also show that the skin performance scales roughly linearly with the number of sensors still active except for the 2 bus case. This is because with only 2 buses there is no way to isolate each sensor on a bus from its neighbors so that losing a bus necessarily creates large sensing gaps. These results show that if bus failure is a concern, at least 3 buses should be used. Beyond that there is a somewhat linear tradeoff between the number of channels in the sensing skin and the skin performance in the case of bus failure. The preferred number of buses depends entirely on the individual application and constraints.

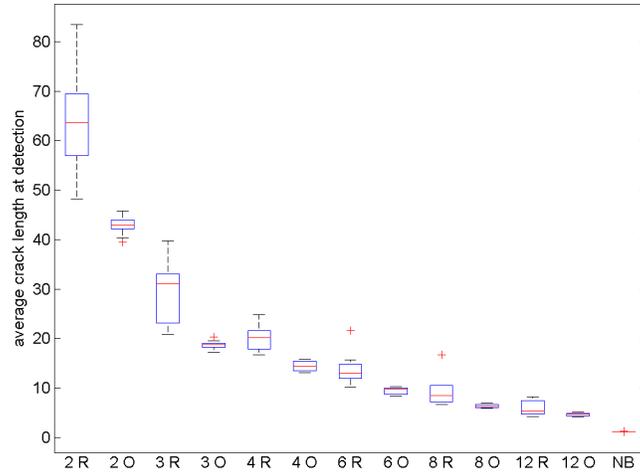


Figure 10: Boxplot results of sensor configuration simulations.

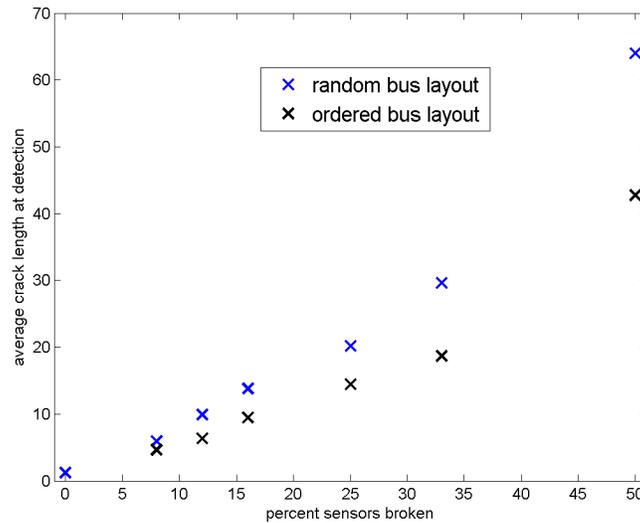


Figure 11: Average crack lengths for several bus configurations.

7. CONCLUSIONS

Crack monitoring skin systems could be a valuable SHM tool in emerging SHM/smart materials applications such as intelligent tamper-indicating seals. In this paper sensor shape was analyzed in order to maximize the crack detection and crack locating abilities for each sensor. In the event that sensors are bussed together to reduce the sensing channel requirements, bus configurations were analyzed to identify ways to make the network robust in the event of a bus failure. Results show that at least 3 busses are desirable to prevent losing sensing capabilities in large segments of a structure. This work is a preliminary effort toward enabling a new class of materials that will be vitally important for future structural health monitoring applications we are referring to as “networked materials.” These are materials for which there are materials properties related to information theoretic concepts. An example material property is “bandwidth” per unit of material that might indicate the amount of information the material can provide about its state-of-health. This work will help provide engineering guidance for designing these materials.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support of the U.S. Department of Energy through the LANL/LDRD Program for this work, grant number 20130527ER. We would also like to acknowledge Karen Miller of Los Alamos National Laboratories for encouraging us to explore the use of smart materials for novel, tamper-indicating seal technology.

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