Smart Structures and Systems, Vol. 5, No. 1 (2009) 43-54

DOI: http://dx.doi.org/10.12989/sss.2009.5.1.043

A decentralized approach to damage localization through smart wireless sensors

Min-Joong Jeong*

e-Science Applied Research Team, Korea Institute of Science and Technology Information, Daejeon, Korea

Bong-Hwan Koh‡

Department of Mechanical Engineering, Dongguk University, 3-26 Pil-dong, Chung-gu, Seoul 100-715, Korea

(Received March 6, 2007, Accepted March 28, 2008)

Abstract. This study introduces a novel approach for locating damage in a structure using wireless sensor system with local level computational capability to alleviate data traffic load on the centralized computation. Smart wireless sensor systems, capable of iterative damage-searching, mimic an optimization process in a decentralized way. The proposed algorithm tries to detect damage in a structure by monitoring abnormal increases in strain measurements from a group of wireless sensors. Initially, this clustering technique provides a reasonably effective sensor placement within a structure. Sensor clustering also assigns a certain number of master sensors in each cluster so that they can constantly monitor the structural health of a structure. By adopting a voting system, a group of wireless sensors iteratively forages for a damage location as they can be activated as needed. Since all of the damage searching process occurs within a small group of wireless sensors, no global control or data traffic to a central system is required. Numerical simulation demonstrates that the newly developed searching algorithm implemented on wireless sensors successfully localizes stiffness damage in a plate through the local level reconfigurable function of smart sensors.

Keywords: damage detection; wireless sensor network; voting system; clustering technique.

1. Introduction

In regard to the safety of load-carrying structures, the last few decades witnessed ever increasing demands of reliable implementation of structural health monitoring (SHM) systems, especially in the fields of mechanical, aerospace, and civil infrastructure (Cawley and Adams 1979). Although there are numerous paths in SHM, recent advances in the field of wireless technology have enabled the combination of micro-scale sensing devices with self-sustainable radio transmitting units (Kling, *et al*. 2005, Mahfuz and Ahmed 2005, Akyildiz, *et al.* 2002). Wireless networking allows the transition from a tethered serial-type sensor to a parallel wireless sensor cluster, which means massive central data processing and cabling instrumentation can be bypassed (Kottapalli, *et al*. 2003, Caffrey, 2004, Lynch

*Senior Researcher
‡Assistant Professor, Corresponding Author, E-mail: bkoh@dongguk.edu

2004, Lynch, *et al*. 2004, Glaser 2004, Xu, *et al*. 2004, Pakzad and Fenves 2004, Clayton, *et al*. 2005, Yuan, *et al*. 2006). The biggest challenge in applying a wireless sensor network to SHM is found in the practical limitations of the battery life of individual sensor nodes. So far, optimal usage of power resources is the only solution for power management in a wireless sensor system, which can be achieved by maintaining an extremely low duty-cycle. If a large number of wireless sensors are randomly deployed and the duty-cycle of each sensor is arbitrarily initiated, then at least a certain number of activated sensors will always be monitoring the global condition of the structural health. In order to maximize the monitoring efficiency of a wireless smart sensor system without compromising power management, the individually measured data from each sensor node should be collectively shared by neighboring sensors. A system-wide, active sensor group provides an early-surveillance mode while inactive (sleeping mode) sensors potentially deliver comprehensive damage tracking. Therefore, proper transition of these two modes will together complete an autonomous SHM system. For example, strain sensors can be deployed in high densities, but are mostly dormant unless the threshold of an error signal significantly exceeds the normal level. Activation of sensor members in a group will be achieved through wireless communication (triggering) between sensor nodes. This objective is easily realized by the IEEE 802.15.4 standard, which includes a medium access control (MAC) layer for this purpose (Zhao and Guibas 2004).

One of the goals of this study is to develop an algorithm using both theoretical and heuristic functions relating to the functional transition of wireless sensors between active and inactive modes. For this goal, this study begins under two assumptions: First, all the sensors are scheduled to switch from sleeping mode to duty mode in a random manner. However, for energy saving purposes, the duration of the sleeping mode is set to be much longer than that of the sensing mode. Thus, only a limited number of sensors are actually awake while all the other sensors are asleep. The second assumption is that each wireless sensor can only communicate with the nearest neighboring sensor. Here, the communication means triggering (activating) the other sensor from sleeping to duty (sensing) mode and transmitting the collected data to neighboring sensors. Therefore, measured data is transferred from point a to b through a multi-hop network. This study explains the procedural steps for the initial clustering of massively distributed wireless sensors followed by a numerical simulation of a plate structure having a stiffness-reducing damage. It will be shown that a concise and logical algorithm enables a small set of local wireless sensors to progressively search for the correct location of damage without relying on any type of global communication or control.

2. Wireless sensor clustering for damage localization

This section introduces the underlying theory and computational steps for implementing a decentralized structural health monitoring system through a wireless sensor system. First, the concept of sensor clustering is explained, which is a crucial step for the success of damage detection. For example, the whole surface of a structure should be divided into several sub-domains in order to assign an appropriate duty-cycle for each sensor node. The number of sub-domains and their geometrical boundaries significantly affects the success of the initial guess for detecting the damage occurrence. Having confirmed the presence of damage, the second part of the section illustrates the computational steps for the damage tracking process and ad hoc communication among the nearest sensors. Finally, switching and regrouping the logic for a master sensor and its neighbors are explained.

2.1. Sensor clustering

It begins with the assumption that n numbers of sensors are randomly deployed and implemented over a finite plane domain. The minimum distance between each sensor, or notably S_{min}, is predetermined so that none of the sensors physically occupy the same location. Here, the i-th sensor is denoted as $x_i = (x_{i1}, x_{i2})$ where x_{i1} and x_{i2} are Cartesian coordinates of the domain. Thus, the distance between sensors i and j is defined as:

$$dis(x_i, x_j) = [(x_i - x_j)^T(x_i - x_j)]^{\frac{1}{2}} \text{ and } i, j = 1, 2, \ldots, n \quad (1)$$

Also, note that if $i \neq j$, then $dis(i, j) > S_{min}$. Figure 1 illustrates the locations of all 679 wireless sensors randomly deployed in the 100 m × 100 m plane area, where S_{min} is limited to 3 m. To minimize the power expenditure of a wireless sensor node involved in data processing and transmission, one can schedule only a small number of sensors in the entire population to be in the active (sensing) mode while the other sensors are in sleep (watch-dog) mode. This can be achieved by randomly initiating the duty-cycle for each sensor node, which will statistically guarantee that some number of sensors are in sensing mode at all times. However, it is still possible that some of the covered areas of the activated sensors are seriously biased to a specific region of the structure, which is undesirable for the robustness of a structural health monitoring system. Fig. 1 shows four randomly selected active sensors out of a total of 679 nodes, illustrating the biased sensor locations. At least some sensors should always be covering the most critical areas of a structure. Thus, it is important to incorporate a clustering technique to divide the overall areas into several sub-domains where at least one of the sensors are guaranteed to be in duty mode at all times. This will avoid extreme bias of active sensor locations in a global perspective. Within a sub-domain, each sensor randomly initiates its duty-cycle.

This study employs the K-means clustering algorithm (Jain and Dubes 1989, Mirkin 1996) for sensor

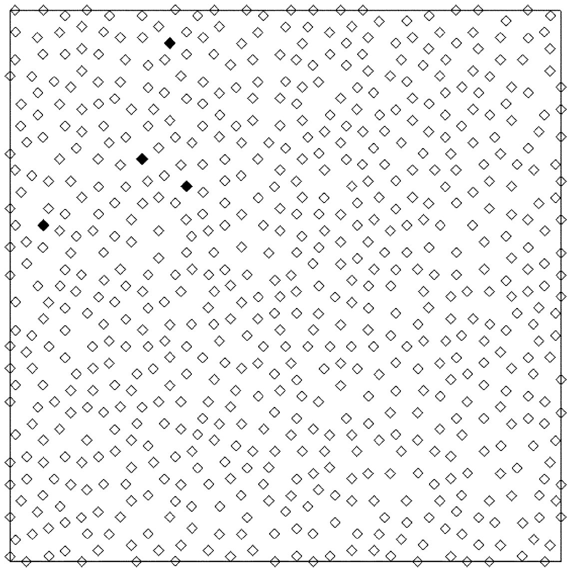

Fig. 1 Four master sensors are randomly selected out of total 679 sensors (hollow diamond). The minimum distance between neighboring sensors is limited to 3 m

grouping. Once K numbers of sensor clusters are created, the central sensor, v_k, can be defined for each cluster as shown in the following:

$$v_k \in \{x_1, x_2, \ldots, x_n\},\ v_k = (v_{k1}, v_{k2}) \tag{2}$$

First, sensor clustering begins by randomly selecting $v_1, v_2, \ldots, v_k$ out of all n sensors (Step 1). The Euclidian distance between central sensors $(v_1, v_2, \ldots, v_k)$ and other sensors (x_i) determines the degree of membership of a cluster (U_{ik}) as shown in Eq. (2) (Step 2).

$$U_{ik} = \left[\sum_{j=1}^{k}\left(\frac{dis(x_i, v_k)}{dis(x_i, v_j)}\right)^{1/(1-m)}\right]^{-1} \tag{3}$$

Here, U_{ik} indicates that sensor x_i belongs to cluster k and parameter m denotes the fuzziness index (Höppner, *et al*. 1999). In this study we use $m = 1$ so that U_{ik} goes to either 0 or 1. Having obtained the membership degree, the next step is determining the pseudo-center, v_k^* as shown below (Step 3):

$$v_k^* = \left(\frac{\left(\sum_{i=1}^{n} U_{ik}\right)\cdot x_{i1}}{\sum_{i=1}^{n} U_{ik}}, \frac{\left(\sum_{i=1}^{n} U_{ik}\right)\cdot x_{i2}}{\sum_{i=1}^{n} U_{ik}}\right) \tag{4}$$

Replace the central sensor v_k with x_i, which is the closest sensor to the pseudo-center v_k^* (Step 4). In other words, when $dis(x_i, v_k^*)$ reaches a minimum value, x_i become v_k. For sensor clustering, step 2 through step 4 needs to be repeated until $v_1, v_2, \ldots, v_k$ converge. Fig. 2 illustrates the simulation results

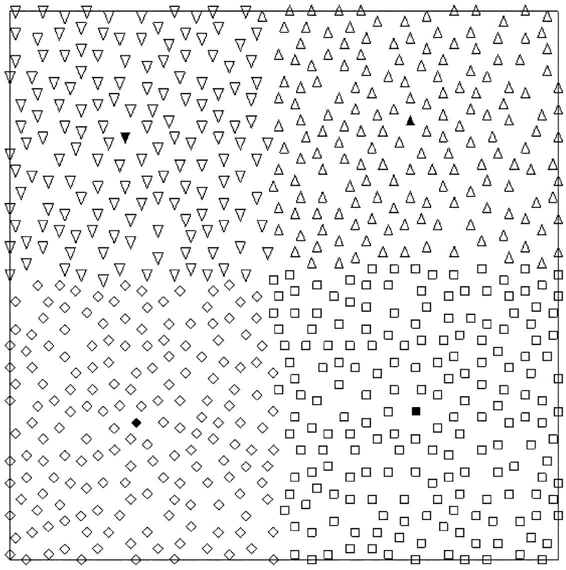

Fig. 2 Four clusters *A* (upper triangle), *B* (square), *C* (diamond), *D* (low triangle) and a master sensor (solid) for each cluster are assigned after 8 iterations

that create four ($K = 4$) sensor clusters where the central sensors are positioned in a rectangular plate among the randomly deployed 679 wireless sensors. The proposed algorithm successfully creates four sensor clusters within six iterations. Comparison between Fig. 1 and 2 clearly shows the benefit of sensor clustering.

2.2. Sensor communication process

If damage occurs in a structure, one of the sensors near the damaged area will pick up the abnormal signal, which is distinguishable from that of a healthy state. However, it is very unlikely that one of the activated sensors happened to be located in the vicinity of the damaged area. Moreover, all the sensor nodes have to maintain an extremely low duty-cycle for optimal power usage. Considering power resources and bandwidth limitation, it is reasonable to assume that each wireless sensor should transmit its measured data to its nearest neighbor. Thus, it is necessary to develop a network protocol where a wireless sensor autonomously sends a wake-up call or activation signal to the nearest sleeping node if the active sensor picks up any measured structural data that is over the threshold value that determines the occurrence of damage. More specifically, if one of the master sensors in a cluster finds irregularities in the sensed data during its duty time, the master sensor needs to activate other sleeping sensors nearby for further interrogation. In this process, the initially activated sensor is denoted as a master and the newly activated sensor as a neighbor sensor. Activated neighbor sensors begin to collect damage sensitive data and transmit their new sensor readings to the master sensor. Having collected all the information from the neighbor sensors, the master sensor must predict the direction of the damage location. Repeating this activation loop allows a small group of sensors to follow the steepest gradient of the contour for the damage-sensitive sensor readings and constantly propagate towards the peak of its intensity. Eventually, activated sensors will completely encompass the damaged area until no further variation or gradient difference in the signal intensity exists among them. Having identified the correct location of the damaged area, the final task for the sensor group is to issue a warning signal to a host station or human inspector for further investigation. There are many ways to indicate the presence of damage. For example, back propagating the information of sensor ID tags to the base station via signal relay, or an even simpler way would be to install a flashing lamp in the sensor node so that an inspector can easily identify the location. It should be noted that all communication between sensors occurs only between the nearest sensors in a group for practical constraints such as power usage and limited bandwidth.

2.3. Damage detection

Following the computational steps illustrates the process of damage detection and the localization algorithm when given a structure equipped with a smart wireless sensor system. Since the proposed detection algorithm consists of an iterative function evaluation and the reproduction of valid (active) sensors, it is similar to an evolutionary search algorithm (Höppner, *et al*. 1999), such as genetic algorithms (Bäck 1996) and evolutionary strategies (Goldberg 1989).

■ Step 1: From the results of sensor clustering in section 2.1, an individual sensor will randomly initiate its duty-cycle, i.e., change from sleeping to active mode within its cluster. The duty-cycle can be adjusted so that, statistically, at least K numbers of sensors are always on-duty at all times.

■ Step 2: Given F_i as the sensor reading to be used for determining damage occurrence within the coverage of sensor x_i, the $F_i > F_{threshold}$ condition triggers the sensor, x_i, to become the master sensor, x_i^*.

This condition will also activate neighbor sensors, i.e., newly selected master sensor, x_i^*, sends a wake-up call to all the sleeping nodes nearby.

■ Step 3: Each sensor node that receives the wake-up call from x_i^* switches to a duty mode and starts to collect data from its sensor module. The measured data will be processed by an on-board microprocessor in each sensor node to further extract a damage-sensitive parameter. This parameter, F_i, will be sent back to its master sensor, x_i^*.

■ Step 4: Having received all the data from active sensors nearby, the master sensor in each cluster compares F_i, including its own F_i^*, and decides whether to surrender its master sensor authority. The master sensor authority includes transmitting wake-up calls to the neighbors and compares the measured data from active sensors. The master sensor has to surrender its authority to any neighbor sensor that has the biggest value of F within the sensor coverage (SC). At the same time, the old master sensor sends a last command call to all other sensors to put them in a sleep mode including the master sensor itself so that the newly selected master sensor can perform its job as described in Step 3. Here, $dis(x^*, x_j) < SC$ and, $j = 1,2,..., n$.

■ Step 5: Iterate Step 2 through Step 4 until x_i^* does not change to another sensor.

■ Step 6: Finally, the master sensor initiates an alarming procedure so that it can transmit the information of the damage location to the base station, if no additional iteration will change the status of the master sensor in Step 5.

The flowchart in Fig. 3 describes the overall process of wireless sensor based decentralized damage detection, which summarizes aforementioned computational steps. It should be noted that sensor placement is an important task that has many factors to be considered such as detecting and networking range, physical obstacles, and installation expenses. However, this study only considers the physical distance between individual sensors and the placement is performed by a clustering technique that enabled a uniformly distributed sensor location. Once all the sensors are in position, a clustering technique divides all the sensors into several groups to prevent an undesirable bias in monitoring

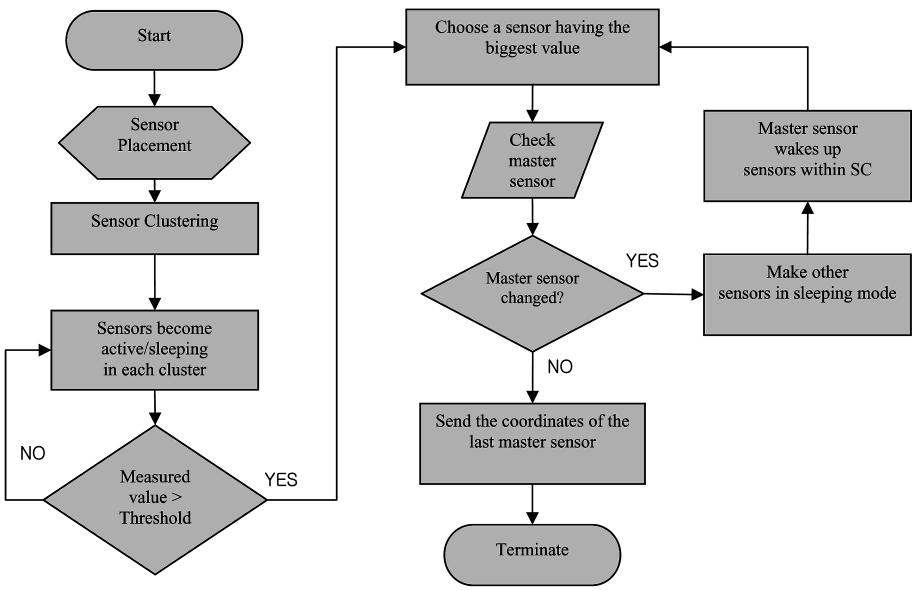

Fig. 3 Overall flow chart for decentralized damage detection procedure

coverage. In most cases, the decision making process simply compares the larger values. Thus, the microprocessor module in each sensor node only needs to hold a concise and straightforward logic to realize the autonomous damage tracking task.

3. Numerical simulation

In this section, we use a Finite Element (FE) model to demonstrate the performance of a wireless decentralized damage detection algorithm as introduced in the previous section. Fig. 4 shows a plate that is 25 m long, 20 m wide and 0.5 m thick. The elastic modulus of the plate is 21×10^6 N/m^2. First, the sensor clustering must satisfy the constraints of providing a physical distance between sensors. Here, we imposed a minimum distance of 2.5 m between sensors. The clustering process is successfully converged within six iterations, placing sensors and dividing the overall area of the plate into four groups (*A~D*) as shown in Fig. 5. Each cluster has at least one master sensor on duty mode at all times. The master sensors, denoted as a solid mark in the figure, become the starting point of damage detection. The master sensor in each cluster activates its neighbor sensor nodes to collect the measured strain values.

It is assumed that structural damage occurs at two elements out of total of 900 finite elements in the model. Using commercial package ABAQUS, a stress analysis is performed. Specifically, reducing the elastic modulus of two damaged elements by 50% creates an eccentric stress profile in the plate where the two lateral edges are subjected to an equal tension of 5 kN/m. Boundary conditions on the upper and lower edges allows for the free expansion of the plate in the lateral direction. Fig. 6 illustrates the contour of von Mises stress on the plate that was caused by damages at two elements located in the middle of the plate. Apparently, the stress concentration occurs on the edge of the damaged elements and its contour develops around them. The analysis results reveal that the maximum plane stress on the damaged edge amounts to roughly 56 MPa. It should be noted that only some of the strongest stress

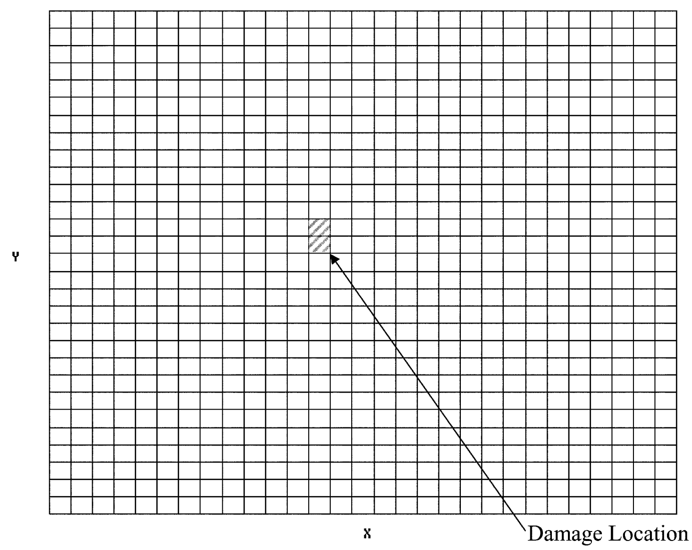

Fig. 4 ABAQUS FE model of a plate (25 m×20 m×0.5 m) having two stiffness-reduced elements out of total 990 elements to simulate the stress condition of a damaged structure

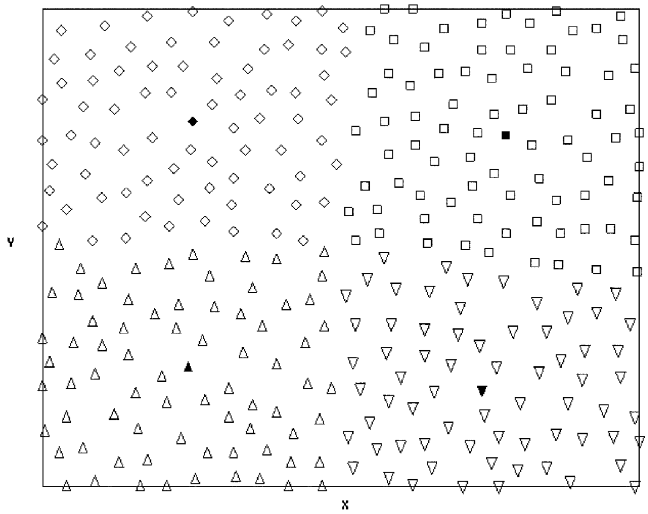

Fig. 5 Four clusters *A* (upper triangle), *B* (square), *C* (diamond), *D* (low triangle) and four master sensors (solid) are assigned out of total 300 sensors over the plate. The minimum distance between neighboring sensors is limited to 2.5 m

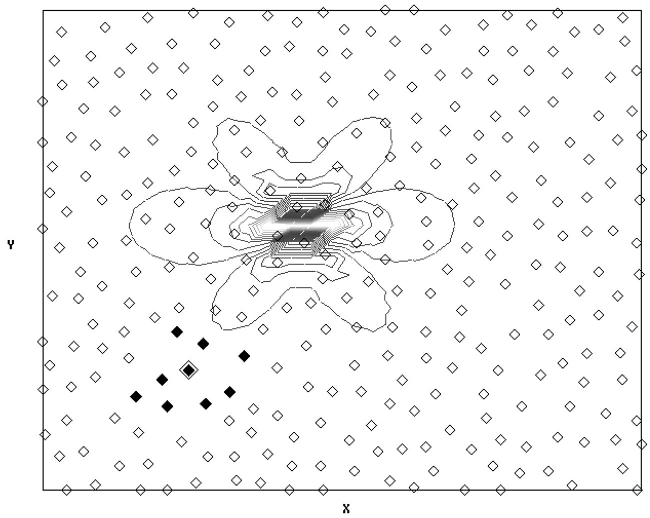

Fig. 6 True damage location is distinguished by von Mises stress contours generated by ABAQUS FE simulation. Initial stage of damage tracking process: one of the mater sensors (double diamond) activates 8 neighboring sensors (solid diamond). Activated sensors communicate each other to find the biggest gradient of measured strain value

contours are visually expressed in the figure, meaning every sensor in the plate can detect strain value changes at all different levels after the damage occurs. Here, we assume that the excessive stress concentration, which typically occurs at a singular point or crack vicinity, is the damage to be detected in order to maintain the health of a structure. The measured strain value from an individual wireless sensor serves as a damage evident feature because the damage detection approach introduced in this paper relies on the computing and networking functionality of off-the-shelf wireless sensors mounted on the surface of a structure. In the end, detecting an unusual increase in strain value from a strain sensor confirms the presence of damage in a structure.

As shown in Fig. 6, the master sensor in cluster *A* (upper triangle) found that the measured strain value exceeded the predetermined threshold, which activated adjacent sensor groups and readied them in sensing mode (Step 3 in Section 3). Note that one master sensor is surrounded by eight active neighbor sensors, forming a perimeter group for damage search. The threshold of the strain value could be predetermined based on the crack stability results of damage tolerance analysis. It is possible that all of the master sensors in all clusters find that the measured strain simultaneously exceeds the preset value, resulting in multiple initiation of the damage localization process. However, this will not cause problems because the activated sensor group led by each master sensor in the cluster will eventually be infiltrated and integrated as a single frontier group while they are searching for the true damage location. Fig. 6 through 8 illustrates the sequential tracking processes in searching for the optimal point or damage origin. If the measured strain value exceeds a certain threshold, the master sensor in each cluster alerts four of the nearest standby sensors constituting an activated monitoring group as represented by solid diamonds in Fig. 6. Note that the master sensor is denoted as a double diamond in the figure. A simple decision-making logic needs to be implemented in each sensor node, i.e., performing pair comparisons between their sensor readings. This pair comparison decides which sensor becomes a master sensor in the following time step. As soon as newly elected master sensor begins to collect the measured data, all other sensors in the group become inactivated and change to sleeping mode. Thus, local sensors constantly vote for a new master sensor in its group by comparing their maximum sensor readings. This voting system serves as an efficient searching strategy and a powerful driving device for autonomous damage tracking. It is obvious that constantly updating the candidate for the master sensor's role and waking its neighbor sensors eventually narrows down the true location of the unknown damage without relying on centralized data traffic to a remote host station. The iterative damage tracking loop ends after an on-duty sensor group completely encompassed the correct location

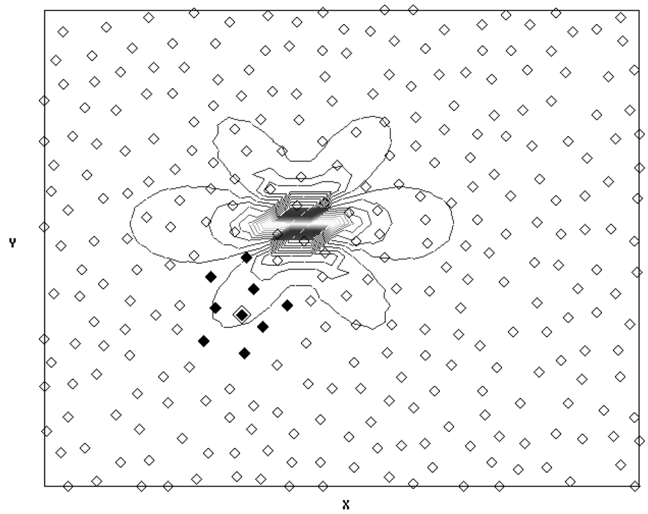

Fig. 7 True damage location is distinguished by von Mises stress contours generated by ABAQUS FE simulation. Initial stage of damage tracking process: one of the mater sensors (double diamond) activates 8 neighboring sensors (solid diamond). Activated sensors communicate each other to find the biggest gradient of measured strain value

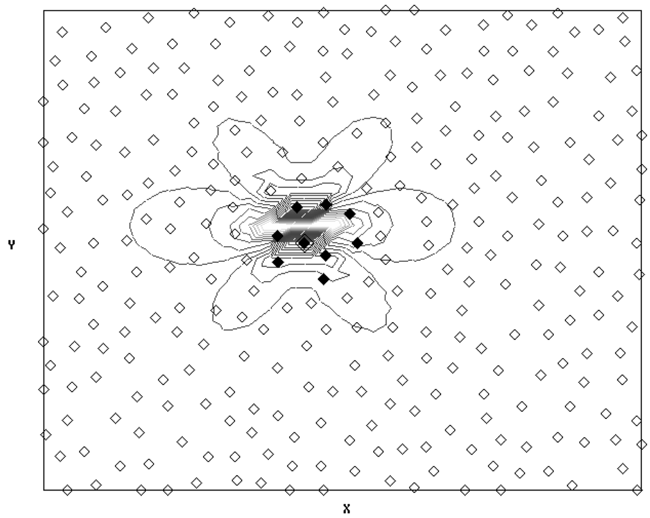

Fig. 8 After five iterations of damage tracking process: mater sensor (double diamond) does not activate neighboring sensors (solid diamond) any longer because no more gradient can be found

of damage as shown in Fig. 8. At this point, the master sensor finds no measured strain value from its neighboring sensors that exceed its own measured data.

The aforementioned damage detection scheme shares its underlying theory with the steepest decent method typically used in optimization algorithms. The main concept of the peak-searching strategy in decentralized damage detection can be implemented by a multi-hop wireless network. The clear advantage of this approach lies in the fact that no central data aggregation or global control of individual sensor nodes is required. Every sensor communication in this approach only needs the smallest data transmission within the nearest sensor node. This cost effective, individual sensor system equipped with powerful computational resources allows the realization of this autonomous damage detection and tracking system within a manageable budget. Particularly, sensor communication refers to a simple pair-comparison between digitized data from two sensors. It should be also noted that the proposed approach only implementable for detecting and localizing the damage-induced strain increase. Recognizing that experimental verification is required in future investigations, the presented study focuses more on numerical simulation of the exploited computational capabilities for off-the-shelf wireless sensor systems in the structural damage detection problem.

4. Conclusions

This research demonstrates the potential capability of a wireless sensor system implemented for decentralized structural health monitoring. A wireless sensor network combined with a sensor clustering technique provides an effective tool for locating structural damage without relying on centralized data processing or communication. First, the clustering technique divides all the sensors into several sub-groups where a master sensor activates neighbor sensors as the measured strain value exceeds a predetermined threshold indicating damage occurrence within a structure. Iteratively changing the role of master sensor among the activated sensor group effectively localizes the structural damage, similar to the steepest gradient searching in an optimization problem. The proposed approach exploits the intrinsically decentralized technique, i.e., only allowing data communication between the physically closest sensors, which is critical to the success of a coarsely populated, multi-hop wireless sensor network. The perimeter line of a sensor group searching for the steepest gradient in a damage-sensitive structural response, eventually encompasses the true location of the damage. An exemplary numerical simulation using a plate FE model provides the potential success of adopting a wireless sensor system to an autonomous damage detection problem. Minimal data communication between the nearest sensors casts a new paradigm for realizing a power-efficient, intelligent wireless sensors system. The preliminary study introduced in this work intends to explore the implementation of an autonomous SHM system to civil infrastructure through simple, inexpensive and unattended wireless sensors deployed in large quantities.

References

Akyildiz, I. F., Su, W., Sankarasubramaniam, Y. and Cayirci, E. (2002), "Wireless sensor networks: a survey", *Computer Networks*, **38**, 392-422.

Bäck, T. (1996), *Evolution Algorithms in Theory and Practice*, Oxford University Press, New York.

Caffrey, J., Govindan, R., Johnson, E. A., Krishnamachari, B., Masri, S., Sukhatme, G., Chintalapudi, K. K., Dantu, K., Rangwala, S., Sridharan, A., Xu, N. and Zuniga, M. (2004), "Networked sensing for structural health monitoring", *Proceedings of the 4th International Workshop on Structural Control*, Columbia University, NY.

Cawley, P. and Adams, R. D. (1979), "The localization of defects in structures from measurements of natural frequencies", *J. Strain Analysis*, **14**, 49-57.

Clayton, E. H., Koh, B. H., Xing, G., Fok, L., Dyke, S. J. and Lu, C. (2005), "Damage detection and correlation-based localisation using wireless sensor mote sensors", *Proceedings of the 13th Mediterranean Conference on Control and Automation*.

Glaser, S. D. (2004), "Some real-world applications of wireless sensor nodes", *SPIE Symposium on Smart Structures & Materials: NDE 2004*, San Diego, CA, March 14-18.

Goldberg, D. E. (1989), *Genetic Algorithms in Search Optimization and Machine Learning*, Addison-Wesley, Reading, MA.

Höppner, F., Klawonn, F., Kruse, R. and Runkler, T. (1999), *Fuzzy cluster analysis*, John Wiley & Sons Ltd, West Sussex, England.

Jain, A. K. and Dubes, R. C. (1989), *Algorithms for Clustering Data*, Prentice-Hall, Englewood Cliffs, New Jersey.

Kling, R., Adler, R., Huang, J., Hummel, V. and Nachman, L. (2005), "Intel mote-based sensor networks", *Struct. Control Health Monit.*, **12**(3-4), 469-479.

Koh, B. H. and Dyke, S. J. (2007), "Structural health monitoring for flexible bridge structures using correlation and sensitivity of modal data", *Comput. Struct.*, **85**(3-4), 117-130.

Kottapalli, V. A., Kiremidjian, A. S., Lynch, J. P., Carryer, E., Kenny, T. W., Law, K. H. and Lei, Y. (2003), "Two-tiered wireless sensor network architecture for structural health monitoring", *SPIE's 10th Annual International Symposium on Smart Structures & Materials*, San Diego, CA, March 2-6.

Lynch, J. P. (2004), "Overview of wireless sensors for real-time health monitoring of civil structures", *Proceedings of the 4th International Workshop on Structural Control*, pp. 189-194, Columbia University, NY.

Lynch, J. P., Wang, Y., Sundararjan, A., Law, K. H. and Kiremidjian, A. S. (2004), "Wireless sensing for structural health monitoring of civil structures", *Proceedings of International Workshop on Integrated Life-Cycle Management of Infrastructures*, Hong Kong, December 9-11.

Mahfuz, M. U. and Ahmed, K. M. (2005), "A review of micro-nano scale wireless sensor networks for environmental protection: Prospects and challenges", *Science and Technology of Advanced Materials*, **6**, 302-306.

Mirkin, B. (1996), *Mathematical Classification and Clustering,* Kluwer Academic Publishers, New York.

Pakzad, S. N. and Fenves, G. L. (2004), "Structural health monitoring applications using MEMS sensor networks", *Proceedings of the 4th International Workshop on Structural Control*, pp. 47-56, Columbia University, NY.

Schütz, M. and Schwefel, H. P. (2000), "Evolutionary approaches to solve three challenging engineering tasks", *Comput. Methods Appl. Mech. Eng.*, **186**, 141-170.

Xu, N., Rangwala, S., Chintalapudi, K. K., Ganesan, D., Broad, A. and Estrin, D. (2004), "A wireless sensor network for structural health monitoring", *Proceedings of the 2nd ACM Conference on Embedded Networked Sensor Systems* (SenSys'04).

Yuan, S., Lai, X., Zhao, X., Xu, X. and Zhang, L. (2006), "Distributed structural health monitoring system based on smart wireless sensor and multi-agent technology", *Smart Mater. Struct.*, **15**, 1-8.

Zhao, F. and Guibas, L. (2004), *Wireless Sensor Networks: An Information Processing Approach*, Morgan Kaufmann.

CC