Numerical simulation of structural damage localization through decentralized wireless sensors

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ABSTRACT

The proposed algorithm tries to localize damage in a structure by monitoring abnormal increases in strain measurements from a group of wireless sensors. Initially, this clustering technique provides an 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. 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.

1. Introduction

The goal of this study is to develop an algorithm using both theoretical and heuristic functions relating to the functional transition of wireless sensor system [1~5] 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

2.1 Sensor Clustering

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.

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:

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

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 $100m \times 100m$ plane area, where $S_{\min}$ is limited to $3m$. 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

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region of the structure, which is undesirable for the robustness of a structural health monitoring system. Figure 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.

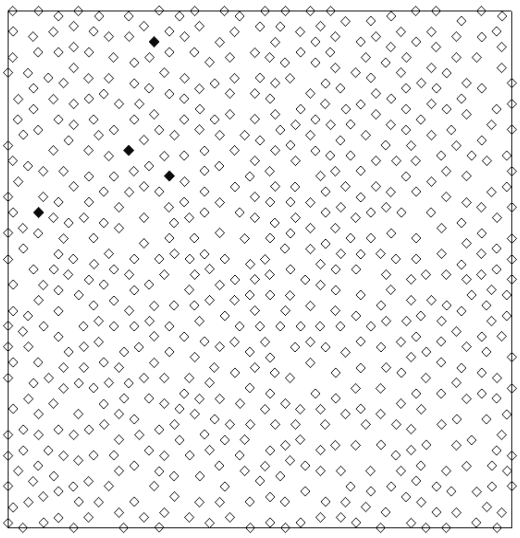

Figure 1. Four master sensors are randomly selected out of total 679 sensors (hollow diamond). The minimum distance between neighboring sensors is limited to 3m.

This study employs the *K*-means clustering algorithm [6, 7] for sensor 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:

$$v_k \in \left\{x_1, x_2, \cdots, x_n\right\}, \quad v_k = \left(v_{k1}, v_{k2}\right) \tag{2}$$

First, sensor clustering begins by randomly selecting $v_1, v_2, \cdots, v_k$ out of all n sensors (Step 1). The Euclidian distance between central sensors ($v_1, v_2, \cdots, v_k$) 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 [8]. 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):

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

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 $v_1, v_2, \cdots, v_k$ converge. Figure 2 illustrates the simulation results 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 Figure 1 and 2 clearly shows the benefit of sensor clustering.

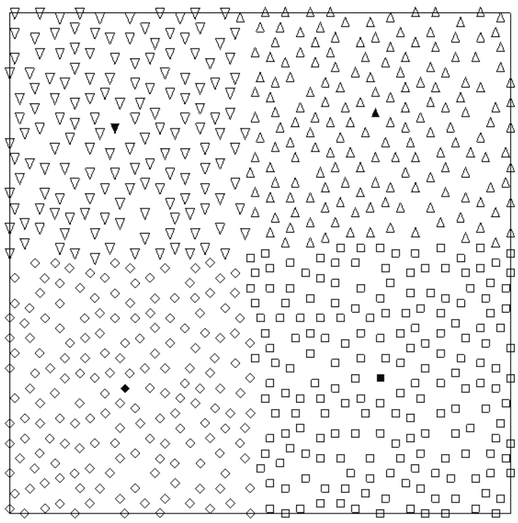

Figure 2. Four clusters *A* (upper triangle), *B* (square), *C* (diamond), *D* (low triangle) and a master sensor (solid) for each cluster are assigned after 8 iterations.

2.2 Damage Detection Algorithm

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, such as genetic algorithms.

- 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 $j = 1, 2, \cdots, n$.

- 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.

3. Numerical Simulation

3.1 Finite Element Model

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. Figure 3 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.

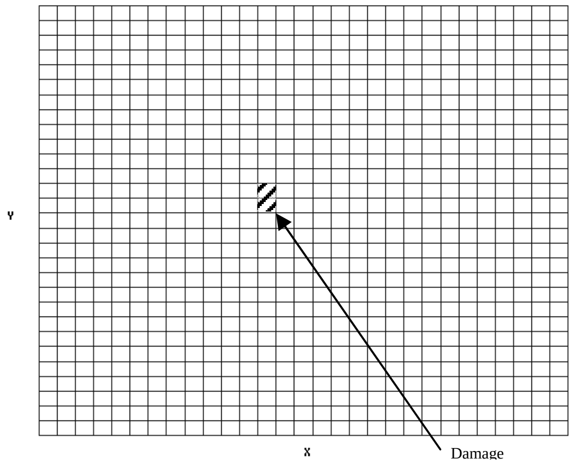

Figure 3. ABAQUS FE model of a plate (25*m*×20*m*×0.5*m*) having two stiffness-reduced elements out of total 990 elements to simulate the stress condition of a damaged structure.

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 Figure 4. 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.

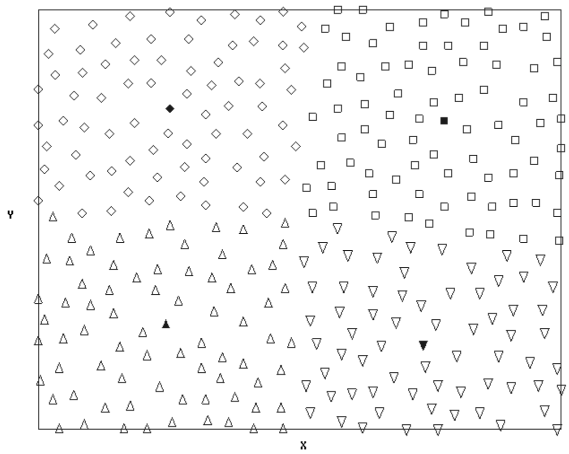

Figure 4. Four clusters *A* (upper triangle), *B* (square), *C* (diamond), *D* (low triangle) and four master sensors (solid) are assigned out of total 300 sensors over the plate. The minimum distance between neighboring sensors is limited to 2.5*m*.

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 5kN/m. Boundary conditions on the upper and lower edges allows for the free expansion of the plate in the lateral direction.

3.2 Damage Tracking Simulation

Figure 5 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 56MPa. It should be noted that only some of the strongest stress 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 [9]. In the end, detecting an unusual increase in strain value from a strain sensor confirms the presence of damage in a structure.

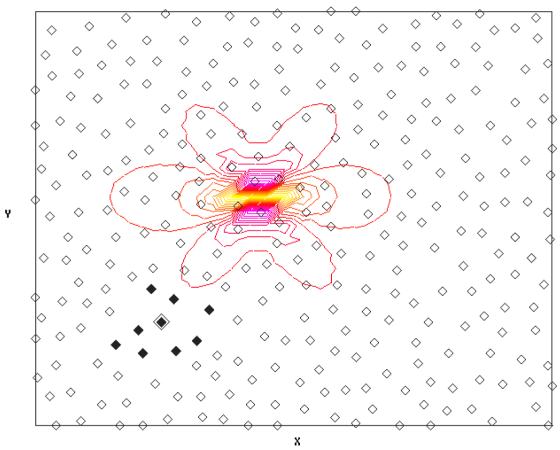

Figure 5. True damage location is distinguished by *von Mises* stress contours generated by ABAQUS FE simulation. Initial stage of damage tracking process: one of the mater sensors (double diamond) activates 8 neighboring sensors (solid diamond). Activated sensors communicate each other to find the biggest gradient of measured strain value.

As shown in Figure 5, 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 2.2). 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.

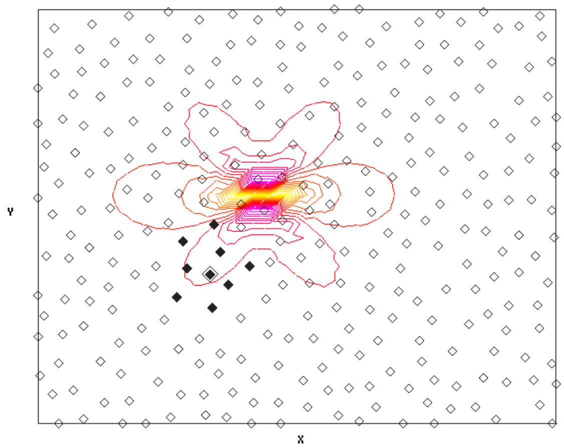

Figure 6. Secondary stage of damage tracking process: one of the mater sensors (double diamond) activates 8 neighboring sensors (solid diamond). Activated sensors communicate each other to find the biggest gradient of measured strain value.

Figure 5 through 7 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 Figure 5. Note that the master sensor is denoted as a double diamond in the figure.

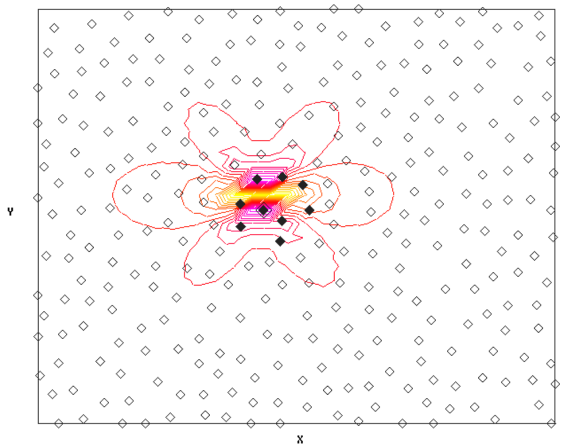

Figure 7. After five iterations of damage tracking process: mater sensor (double diamond) does not activate neighboring sensors (solid diamond) any longer because no more gradient can be found.

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

4. Conclusions

This research demonstrates the potential capability of a wireless sensor system implemented for decentralized structural health monitoring. 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.

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