Smart Sensor Network for Modal Parameter Identification

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ABSTRACT:

Instrumentation is a tool that allows for the monitoring and the dynamic characterization of the structures. This is achieved through the placement of sensor connected to a data acquisition system. The actual data acquisition systems have a wired communication with the sensor's network. For this reason the instrumentation of structures represents high cost of investment, installation and maintenance. As an alternative to this paradigm, this paper presents an implementation of a wireless network of sensors. The first objective is the selection of the best sensor's placement to attain the dynamic characterization. The second goal is to propose a network formation that allows for a better information distribution as well as low power consumption.

INTRODUCTION

One of the principal goals of structural instrumentation is to monitoring its dynamic properties. Also, permit to know the behavior before, during and after the structure is subject to an excitation. The obtained information allows alert over the security conditions, so to schedule the required maintenance operations to safeguard its occupants and structural condition.

In general, the structural instrumentation is not a common practice in the world. Some of the reasons are a) the high installation and maintenance cost, b) the lack of methodologies for adequate instrumentation and, c) the lack of knowledge for the application of the new technologies

Some of the benefits of structural instrumentation are: a) determination of the dynamic properties, b) knowledge of the behavior in service conditions, c) monitoring of the structural performance at induced excitations, d) detection of potential danger due to the damage in the structure and, e) security revision of the structures design with previous regulation. Furthermore, the information collected from the monitoring of the structures can be use for hypothesis verification and results of diverse mathematic models, in particular those concerning with fine element models. Other benefits are the extrapolation

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of the actual response of the structure with respect of that expected during a strong earthquake. Finally, to facilitate the take of decisions over structures that can be rehabilitated.

Wireless networks can be applied to structural systems, these networks pretend to, a) diminish installation and maintenance costs, b) implement a methodology of easy application to any type of civil structure, c) the option of increment the number of sensors over the structure with no impacting in higher costs; all the previous without diminish the benevolence of the wire instrumentation.

To achieve the implementation of network of wireless sensors it is necessary to overcome issues related to the information management, communication between sensors, placement location and number of sensors, among others.

This paper has the following structure; in the first section a brief overview of the methodologies for optimal sensor placement is presented, the following section a definition of distributed algorithms. An analytical implementation on a plane frame is presented and finally a proposal for a network formation is developed.

OPTIMAL SENSOR PLACEMENT METHODOLOGIES

The optimal sensor placement of sensor has been a research topic in the last years. Shah and Udwadia [1] were one of the first in authors in this topic. Their paper investigates the best sensor placement for estimation of dynamic properties; the solution is based on the covariance matrix. Later Udwadia [2] propose a methodology based on the Fisher information matrix that is applicable for linear and nonlinear systems.

Heredia [3] presents guidelines for optimal instrumentation based on the loss of the Bayesian information. Heredia at al. [4] extended their previous work to be applied to structures constructed over soft soil. The goal was to investigate the effects of this type of soil on the instrumentation system.

Ka-Veng et al. [5] presents a methodology to propose optimal and rental systems of sensors for model update, and structural health monitoring. This selection is based in the entropy of the uncertainty information. The methodology determines the number of required sensors and their location based on the desired modal shapes.

Finally, Cherng [6], presents a methodology based on the analytical formulation of singular value decomposition for a candidate-blocker Hankel matrix using Signal Subspace Correlation (SSC). The advantage of using SSC is that takes in account the mode shapes, damping ratios, sampling rate and matrix size. The author proposes two methods that are based on modified versions of the Lim-Gawronski [7] method and Bayard-Hadaegh-Meldrum [8]. The methodology proposed by Cherng [6] was used in this paper.

DISTRUBUTED ALGORITHMS

R. Marcelín [9] define a distributed system as the heterogenic sum of components of hardware, software and data, interconnected by some type of communication network to collaborate in offering a service related to information management. Also, mentions that the difficulties in the construction of these systems are related to the limitations of the components. It is desirable for the system to guarantee the quality of the service, even of a number of the components fails or deviate from the operation specification. The distribute systems can be divided in two main categories:

a) Messaging passing
b) Share memory

The first one emphasizes the role of the communication network. It is described as a non-directed graph G=(V,E), in which the group of nodes V, represents the network processors; and the group of the joints E, represents the bidirectional communication channels that interconnect the machines and where messages are exchange.

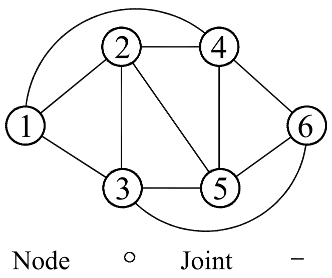

Figure 1: Graph G=(V,E)

In the second category the process communicates carrying out operations of storage and recover of the information over a common organized space of share objects. These objects could be read/write registers, tails or registers with atomic operations of the type test&set

Distributed algorithms can be defined as a recollection of autonomous process that share information for the realization of a common task. Each process that runs its local version of the distributed algorithm can be characterized as a joint of finite process, a finite group of communication events, and a finite group of atomic transactions between states, trigger trough communications events.

SENSOR PLACEMENT

After presenting different approaches for best sensor placement, this paper will use the methodology proposed by Cherng [6]. This integrates two important aspects for optimal sensor placement: the geometric weight of the sensor (its location within the structure), and the obtained data. Furthermore, in this methodology converges some of the criterion studied by other authors. For space reasons only a brief summary of the most important aspects of the methodology is presented.

Lim-Gawronski (LG) approach

Based in the Hankel Singular Values (HSV), the LG method ranks a sensor for its contribution of with respect of the targeted modes. In this sense, each sensor can be evaluated with respect of the total contribution of the set of sensor placement. The total contribution of a sensor placement set is define as the trace of the $\mathbf{H}^T\mathbf{H}$ (where H is the Hankel matrix)

$$\gamma^2 = \mathrm{trace}\left(H^T H\right) \tag{1}$$

$$\gamma_i^2 = \sum_{r=1}^{n} \tilde{\gamma}_{ir}^2 \tag{2}$$

In the equation (2) $\tilde{\gamma}_{ir}^2$ represents the contribution of the *i*th sensor to the *r*th mode, and γ_i^2 represents the contribution of the *i*th sensor over the *n* targeted modes. In matrix form the equation (2) is as follows

$$\Gamma_{LG} = \begin{bmatrix} \bar{\gamma}_{11}^2 & \bar{\gamma}_{12}^2 & \cdots & \bar{\gamma}_{1n}^2 \\ \bar{\gamma}_{21}^2 & \bar{\gamma}_{22}^2 & \cdots & \bar{\gamma}_{2n}^2 \\ \cdots & \cdots & \cdots & \cdots \\ \bar{\gamma}_{m1}^2 & \bar{\gamma}_{m2}^2 & \cdots & \bar{\gamma}_{mn}^2 \end{bmatrix} \tag{3}$$

From equation (3) the rows represent the *m* sensor location over the structure, and columns the *n* targeted modes. So, one element of this matrix is defined as the fractional contribution of the *m* sensor location over the *n* targeted mode.

Bayard-Hadaegh-Meldrum (BHM) approach

The BHM approach has two steps, first adds each modal contribution over all sensor locations, and later ranks the product of the contributions. The square root of the modal determinate of $\mathbf{H}^T\mathbf{H}$ is simply the product of all modal HSV of H.

$$S = \det(H^T H)^{1/2} \propto \psi \tag{4}$$

Where

$$\psi = \det(diag(\Phi^T \Phi)) \tag{5}$$

Equations (4) and (5) indicate that the product of the HSVs, S, are proportional to the placement index ψ, which is also the Fisher Information Matrix of the BHM.

A matrix representation of the equation (5) is

$$\Gamma_{BHM} = \begin{bmatrix} \varphi_{11}^2 & \varphi_{12}^2 & \cdots & \varphi_{1n}^2 \\ \varphi_{21}^2 & \varphi_{22}^2 & \cdots & \varphi_{2n}^2 \\ \cdots & \cdots & \cdots & \cdots \\ \varphi_{m1}^2 & \varphi_{m2}^2 & \cdots & \varphi_{mn}^2 \end{bmatrix} \tag{6}$$

Equation (6) indicates that the modal contribution can be evaluated mode by mode, since the total modal energy is added through all *m* candidate sensor locations.

Difference between LG y BHM approaches

LG approach selects the sensor placement location based on the information collected at sensor with respect to the *n* targeted modes. That is, only takes in account the arithmetic mean without weighing the location of the sensor.

The BHM methodology pick the sensor placement location based on the information of the mode shapes at the *m* sensor location. That is, only takes in account geometric mean without weighting the information of the sensor.

To take advantage of these two methodologies Cherng [6] proposed a strategy for sensor placement using SSC. With this approach the LG and BHM methods can be unified. The first step is to normalize the modes before ranking them.

$$\rho_{ir} = \frac{\varphi_{ir}^2}{\sum_{i=1}^{m} \varphi_{ir}^2} = \bar{\rho}_{ir} \qquad 0 \le \rho_{ir}, \quad \bar{\rho}_{ir} \le 1 \tag{7}$$

where

$$\sum_{i=1}^{m,} \rho_{ir} = 1 \qquad \forall_r \tag{8}$$

Expressing the previous equations in a matrix form

$$\Gamma = \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1n} \\ \rho_{21} & \rho_{22} & \cdots & \rho_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ \rho_{m1} & \rho_{m2} & \cdots & \rho_{mn} \end{bmatrix} = [\rho_1 \quad \rho_2 \quad \rho_3 \quad \rho_4] \tag{9}$$

So, the contribution of the *i*th sensor over all targeted modes is:

$$\rho_i = \sum_{i=1}^{n} \rho_{ir} \qquad 0 \le \rho_i \le n \tag{10}$$

$$\sum_{i=1}^{m} \rho_i = n \tag{11}$$

The ranking of the sensor is based on the ρ_i numerical value.

ANALITYCAL APPLICATION

A planar frame was used for the implementation of this methodology with 90 sensor locations (see figure 2).

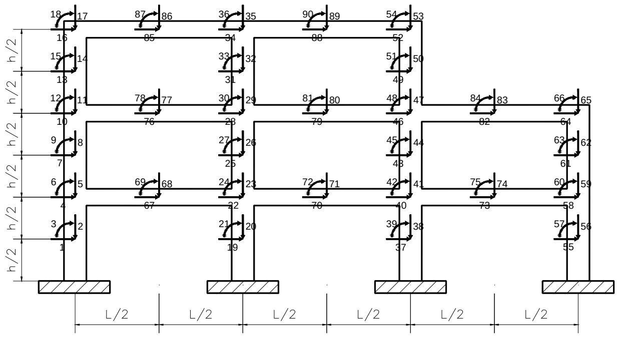

Figure 2: Planar frame with 90 sensor placement locations.

For space reasons, only the selected sensors for *x* direction are shown in table 1. The rotational degrees of freedom were ignored.

Table 1: Sensor's contributions in *x* direction for the first five mode shapes.

DoF	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
4	0.0047	0.0222	0.0008	0.0017	0.0000
7	0.0166	0.0308	0.0004	0.0042	0.0000
10	0.0364	0.0118	0.0004	0.0003	0.0000
13	0.0609	0.0035	0.0001	0.0015	0.0004
16	0.0878	0.0707	0.0016	0.0021	0.0000
22	0.0048	0.0240	0.0017	0.0006	0.0000
25	0.0167	0.0339	0.0045	0.0001	0.0001
28	0.0364	0.0144	0.0002	0.0002	0.0001
31	0.0612	0.0035	0.0022	0.0007	0.0007
34	0.0874	0.0708	0.0015	0.0011	0.0000
40	0.0048	0.0233	0.0007	0.0012	0.0000
43	0.0165	0.0393	0.0003	0.0007	0.0003
46	0.0356	0.0214	0.0001	0.0001	0.0001
49	0.0593	0.0010	0.0011	0.0000	0.0002
52	0.0872	0.0683	0.0007	0.0009	0.0000
61	0.0162	0.0274	0.0055	0.0042	0.0001
64	0.0346	0.0319	0.0000	0.0001	0.0000
67	0.0048	0.0241	0.0013	0.0011	0.0000
70	0.0048	0.0247	0.0012	0.0009	0.0000
73	0.0048	0.0211	0.0017	0.0021	0.0000
76	0.0365	0.0136	0.0003	0.0003	0.0000
79	0.0361	0.0185	0.0002	0.0002	0.0000
82	0.0353	0.0276	0.0000	0.0000	0.0000
85	0.0879	0.0731	0.0016	0.0016	0.0000
88	0.0876	0.0719	0.0012	0.0011	0.0000
$\sum\rho$	**0.96**	**0.77**	**0.03**	**0.03**	**0.00**

SENSOR CONECTIVITY

After selecting the sensor locations five connectivity arrangements were investigated, these are shown in figure 3.

The location of the central node, in which all the information will be concentrated, was also investigated. Five possible positions were selected at nodes: 1, 21, 27, 30 and 33 (see figure 4), named A, B, C, D and E respectively.

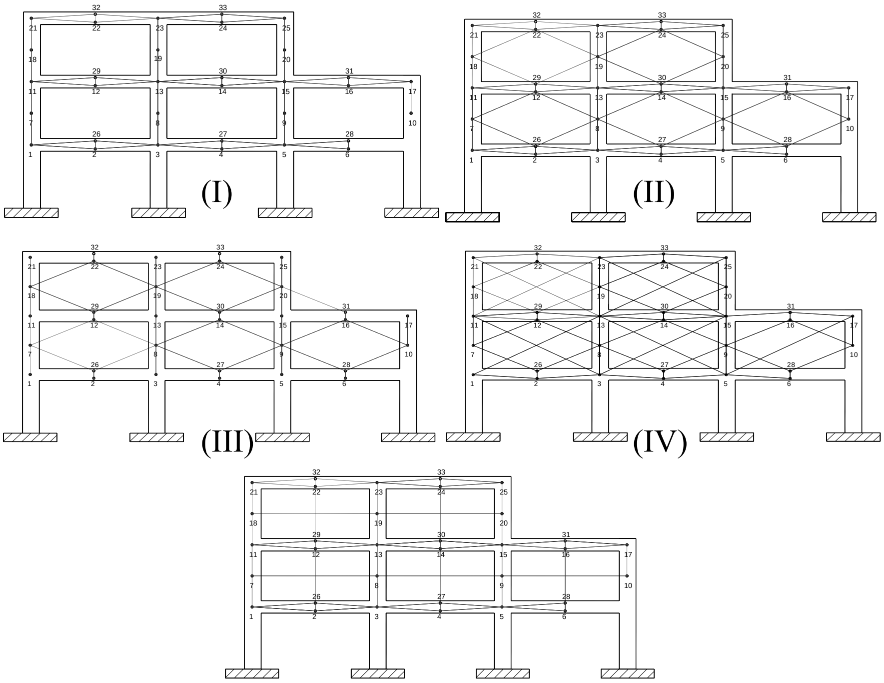

Figure 3: Proposed connectivity trees: (I) through (V).

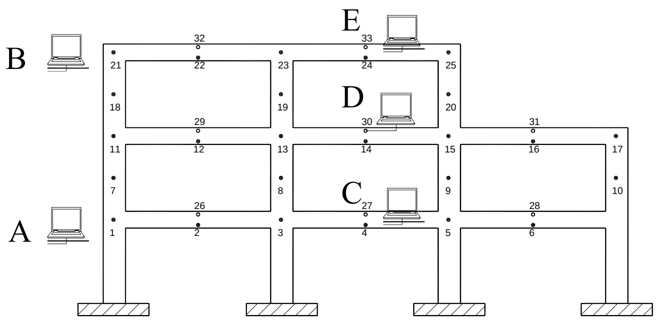

Figure 4: Locations of the central node: A, B, C, D and E

The network formation is proposed based in two techniques: Depth First Search (DFS) and Breadth First Search (BFS). In the DFS method each node recognizes one child and all their de descendants before searching for their next son. The BFS method each node recognize all its children before them seek their descendants.

The DFS is first implemented, this will construct connectivity tree with only one threat. This tree constitutes a layer that will be used to assure that no collisions are presented in the network. Later a BFS is conducted over the network. This layer will be used as route for data retrieval, and will assure the robustness of the network. A computer program was developed to simulate the data transmission in the network. The variables involved were: sweeping period, buffer size, channel bandwidth, bits generated by the sensor.

The sweeping period is the time imposed to the net in which the central node commands to the nodes to send their storage data. Buffer size, channel bandwidth and the bit generated by the sensor were fixed according with the specifications of the Berkeley Mote platform [10]. For space reasons figure 5 only shows the results for the frames III and VI with all five central node locations. The sweeping period was set in 400 seconds.

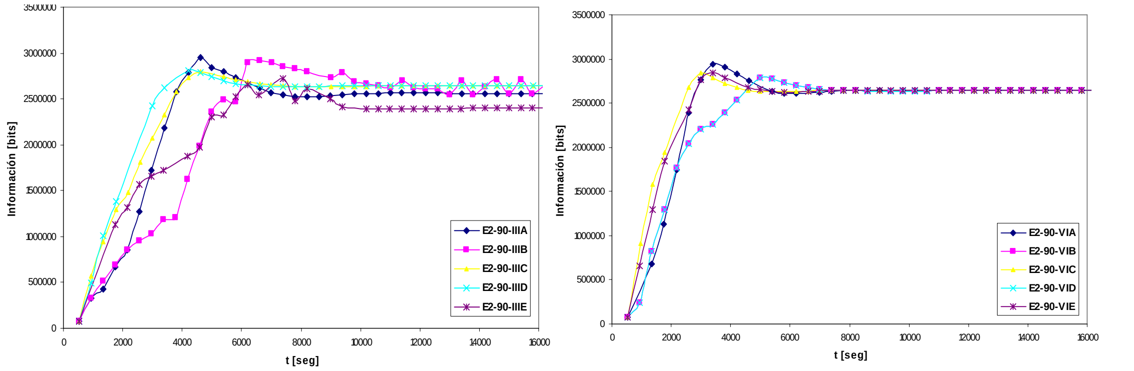

Figure 5: Information bits vs. time

CONCLUSIONS

A methodology for sensor location that combines arithmetic and geometrical mean was implemented in a plane frame. Five interconnection routes and central node locations were studied. A network connectivity methodology that combines the DFS and BFS approaches was developed. Simulations shown that the time required in reaching maximum data collection depends more in the interconnection route than the central node position.

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