Demo: On the High Quality Sensor Placement for Structural Health Monitoring

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***Abstract*—Sensor networks are widely used for structural health monitoring systems today. Existing studies on sensor systems from computer science community seldom take civil and structure factors into consideration. For example, the commonly adopted sensor placement schemes are still assumed to be random or on grids. We release an open source package SPEM, which, working as a black box, can evaluate the locations of sensor placement from the aspects of civil engineering. In this demo, we will first show how this package can be used by a few synthetic examples. We will show its indication for the designs of sensor networks to the computer science community. We will further illustrate SPEM with real structural data collected from our ongoing monitoring project of the Guangzhou New TV Tower.**

I. Introduction

Sensor networks today are commonly used for applications in structure, environment, oceanography, etc. In computer science community, it is well accepted that resource optimization of the sensor systems must be tightly correlated with the respective applications. This is sharply different from the Internet, where the communication system is strictly separated from the above and only sees general packets. Nevertheless, current data aggregation schemes are still preliminary with simple statistics as MEDIAN, AVERAGE, SUM, VARIANCE. Locations of sensor placement are either assumed to be random or on specific grids/trees. These may not be practically meaningful for the respective applications; making the great efforts in the computer science community for developing efficient methods associated with these techniques less useful.

We consider the structural health monitoring (SHM) applications, based on our experience with the development of the monitoring system of the Guangzhou New TV Tower, China (GNTVT [1], See Fig. 2 (a)) and a previous application on the Tsing Ma Bridge, Hong Kong. On the civil side, the highest priority is to transmit all the data sampled by the sensors to the analysis center; and they are less focused (or experienced) on resource optimization in the networking system. As such, some design choices or requirements seem awkward to computer scientists and a joint expertise of both civil engineering and computer science is greatly needed.

Our experience shows that by no means a joint understanding is easy. We take a step forward to merge this gap. We developed an open source, SPEM (Sensor Placement using EFI Model) to compute the locations that the sensors should be deployed on a structure so that the data collected are useful for civil analysis. More specifically, given a set of locations M, and the number of sensors N to be deployed, where $M > N$, SPEM will output a sensor placement scheme that is best for evaluation of the structure properties. SPEM implemented several real evaluation techniques that are widely adopted in civil engineering. The understanding of these techniques, however, is not necessary and it can work as a black box. We hope that SPEM can help to rectify some biased or imagined assumptions made by the computer science community due to lack of knowledge on civil engineering. SPEM is accessible from [2].

In this demo, we will show 1) how to use SPEM; both with synthetic examples and the real data from GNTVT; 2) how some real computer science choices can be integrated with civil engineering by judgment from SPEM. We will also discuss the current development and results of the sensor monitoring system (designed to be life-long, real-time) of the GNTVT (610m in height, to be completed at the end of 2009).

II. Brief Foundation behind SPEM

SPEM is developed in MATLAB and implements two sensor placement methods from structural health evaluation; they are, EFfective Independence (EFI) and EFfective Independence Driving Point Residue (EFI-DPR). We briefly discuss the EFI method [3] which is the most widely accepted sensor placement method.

In civil engineering, each type of mechanical structure has a specific pattern of vibration at a specific frequency. This is called *mode shape*. Mathematically, the mode shapes of a structure form a mode information matrix:

$$\Phi = [\Phi^1, \Phi^2, ..., \Phi^K] = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1K} \\ \vdots & \vdots & \vdots & \vdots \\ a_{M1} & a_{M2} & \dots & a_{MK} \end{bmatrix}.$$

Recovering a higher order of mode shape will lead to more accurate representation of the structure; yet this requests more sensors. Generally, the number of mode shape K to be recovered, the number of possible locations M for sensor placement, and the number of sensors N are fixed in advance (usually $K = 1 - 12$ and $M > N > K$). EFI is an iterative method which remove one location in each iteration. The removal is carried out so that the determinant of a so-called Fisher Information Matrix (FIM) is kept maximized. Intuitively a larger FIM indicates a larger amount of the useful information.

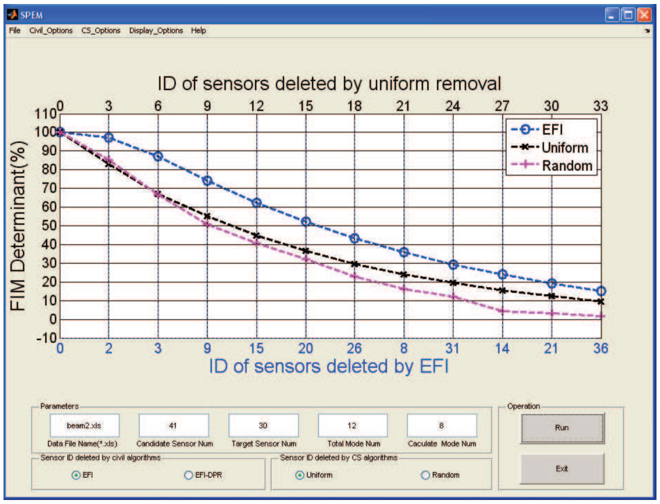

Fig. 1. The graphic user interface of SPEM; and one snapshot of execution.

III. Demo Description

The user interface of SPEM is shown in Fig. 1. This figure also illustrates an example of a placement on a simulated cantilever. There are 41 candidate locations and 30 sensors to be deployed. The user is interested in 8 mode shapes. In such scenario, 11 locations need to be removed. We label all these locations from 1 to 41. The x-axis shows the ID of the locations to be removed after each iteration of SPEM. The y-axis shows the FIM determinant. FIM decreases after each removal as the less of the number of sensors deployed, the less information can be captured in FIM.

In this example, besides the EFI model, we also illustrate two other methods, the random removal and uniform removal. The random removal method is to remove locations at random and the uniform removal method is to remove locations so that the remaining locations are uniformly distributed. Such schemes could be selected by computer scientists with inadequate knowledge of civil engineering. Apparently the FIM of EFI is much larger (thus better) than the other two schemes. Note that after removal of ID 18 by uniform method (removal of 6 sensors), the FIM is the same as the removal of ID 26 by EFI method (removal of 8 sensors). In other words, EFI saves 2 more sensors just by deployment on better locations. Clearly, this shows that the built-in civil aspect by SPEM can assist better development of the networking system.

To further illustrate how SPEM can be used jointly with computer science, we interpret this example in another way. If there are a total of 100 locations that are suitable for sensor deployment, and 30 sensors are available. After optimization from the computer science constraints (e.g., the communication range, power consideration, deployment costs, etc), there are 41 locations left which are considered equivalent (or satisfy some thresholds). SPEM can then be used for the final selection of the 30 locations which can be more meaningful for civil engineering. This example is artificial; nevertheless, it illustrates how the concerns of computer science and civil engineering can be jointed considered.

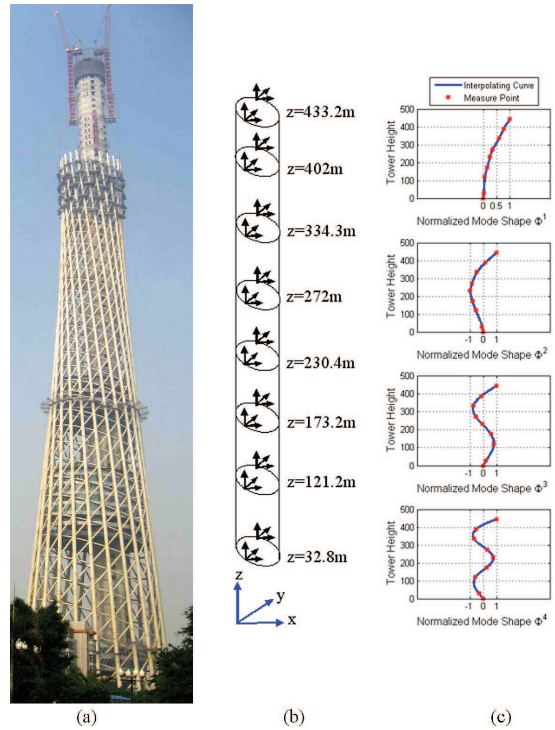

Fig. 2. (a) GNTVT in construction. (b) Trial sensor placement on GNTVT. (c) The 1st, 2nd, 3rd, and 4th mode shape of GNTVT.

We will also show SPEM with some real data from GNTVT. Due to space limitation, in this demo proposal we can only discuss an overview of the GNTVT and how the data are collected so that they can work as an input for SPEM. The data are collected by our in-construction SHM system of GNTVT from 9 p.m. to 22 p.m. on January 16th, 2009. The data in this demo are collected by eight sensor sets installed on eight distinct floors of GNTVT as shown in Fig. 2 (b). Real structure mode shape is extracted using professional vibration analysis software ARTiMIS Extractor.

Though the number of sensors is small, the collected data can successfully rebuild the first four mode shapes of GNTVT (see Fig. 2 (c)), thus the synchronization and accuracy of the data can be considered reliable and sufficient for algorithms evaluations in SPEM; and we will show this in the demo.

With the growth of the tower, more sensors will be included in our SHM system. To the best of our knowledge, we are the first to work on such high-rise real structure (610m in total, 450m so far) and mode shape recovery indicates that our SHM system runs well.

References

[1] Structural Health Monitoring for Guangzhou New TV Tower using Sensor Networks, [online] http://www.cse.polyu.edu.hk/benchmark/

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[3] A. Rao and Ganesh Anandakumar, "Optimal sensor placement techniques for system identification and health monitoring of civil structures", *Smart Structures and Systems*, vol. 4, no. 4, pp. 465-492, 2008.