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# Monitoring Historic Buildings Using Distributed Technologies

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ABSTRACT: In this paper we outline a research program aiming to develop technological tools for real-time assessment of historic buildings. In detail, in our project (1) we will develop an Historical Heritage Management System (HHMS) along with (2) the technological instruments for integrating HHMS with real-time monitoring and control of historical structures, and (3) we will apply a pilot monitoring system, working within this framework, to a case study. HHMS is an online database with web-based instruments for inventory, conservation state assessment, risk evaluation and prioritization of maintenance action. The system is designed for automatic receipt and processing of data streams from permanent monitoring systems. The case study is on the Aquila Gate in Trento. Motes network sensors are the basis of the monitoring systems. Sensors include accelerometers, thermometers and strain gauges. Sensing techniques are selected for integration into the Mote platform and for durability and include both fiber-optics and electrical gauges.

## 1 INTRODUCTION

The safety assessment of buildings requires multidisciplinary skills as well as specific knowledge, and this is especially true when dealing with historic structures. The assessment process typically includes these steps: data acquisition, signal analysis, numerical modeling, safety evaluation, decision making. Often each stage will develop independently of the others and at different times, so that data exchange between the different subjects involved in each task is possible only at the end of the corresponding working phase. Using this procedure, the time-scale between the first experimental data acquisition and final evaluation is in months or years. Here we present the outline of a research program which aims at developing technological tools for turning the above-mentioned process into a real-time operation. The idea is to take advantage of the Internet capabilities and of the new sensor technologies. In detail, in our project (1) we will develop an Historical Heritage Management System (HHMS) along with (2) the technological instruments for integrating HHMS with real-time monitoring and control of historical structures, and (3) we will apply a pilot monitoring system, working within this framework, to a case study.

HHMS is an online database having web-based instruments for inventory, conservation state assessment, risk evaluation and prioritization of action, as described in detail in Section 2. The most interesting feature of the system is its capability of automatic receipt, processing and management of data streams from permanent monitoring systems. The case study chosen for the demonstration is the Aquila Gate, one of the most important historical monuments in Trento. Details of this building are shown in Section 3, while in Section 4 we present the design of the monitoring system. Network sensors of the Mote type have been chosen for local data collection and communication in this system. Sensors include accelerometers, thermometers and strain gauges. Sensing techniques are selected for integration into the Mote platform and for durability and include both fiber-optics and electrical gauges. Possibly the most challenging aspect of the management concept is to combine real-time monitoring, data management and decision making, within the same framework. System operation requires techniques for processing the large amount of data acquired by the monitoring system in elaborate information on the condition of the structure. The general method used for identifying damage is based on Bayes' principle, as described in Section 5.

## 2 HISTORICAL HERITAGE MANAGEMENT SYSTEM

The authors define HHMS as a set of technical instruments, procedures and models that provides the public administration with the necessary information to take decisions for the conservation of the architectural heritage which is under its responsibility. The concept of HHMS clearly originates from that of the Bridge Management System (BMS) which is a tool used by transportation agencies to define the optimal Maintenance, Repair and Reconstruction (MR&R) strategy of their bridge stock. Of course, the objectives of a management system applied to bridges differ from those applied to historic buildings: in the first case the goal is to guarantee safety and reliability of bridges, minimizing life-cycle cost, whereas in the latter case the conservation of the buildings, as well as of the artistic heritage they host, is the main concern. Despite this, it is true that a significant part of the concepts developed for bridges can apply to historic buildings: in both cases an inventory system and a system for appraising the condition of the buildings are required; and in both cases decision making requires statistical models for estimating present and future degradation and the associated risk.

### *2.1 Basis for the classification and structural description of historic buildings*

The purpose of the inventory system is the definition of a standard set of structural and architectural elements that can be treated in homogeneous manner by the system, in order to gain statistical information on the state of conservation and vulnerability of the entire heritage. In defining the inventory system, we attempt to apply, as far as possible, existing inventory systems, codes and standards: and most of the database structure was taken from the Cataloguing Standard issued by the *Central Institute for Catalog and Documentation* (CICD) of the Italian Ministry of Cultural Heritage and Activities (http://www.iccd.beniculturali.it). The aim of CICD is to develop methods and standards for selection and description of our cultural heritage, aimed at creating a general inventory. The standards developed by CICD define the data structure and the set of inventory rules for all types of cultural items, not only to architecture. As for historic buildings, the data includes ownership information, location, history, previous restoration information, and a structural description of the building itself. The conceptual approach is to break down the building into a number of structural components, or elements, which can be objectively recognized and evaluated. Such elements are foundations, vertical structures, horizontal structures, roofs and stairs. Each element is then classified by categories and subcategories: for example elements of the *vertical structures* type include columns and walls; in turn, columns are classified by construction techniques and material, and described in terms of technical specifications. The inventory also includes a number of non-structural elements such as floors and decorations (e.g. frescos).

As for the assessment of the conservation state, we adopted an inspection protocol compatible with that developed by the *Central Institute for Restoration* (CIR) (http://www.icr.beniculturali.it) within the risk map project. The ICR Risk Map is an evolving geographic information system (GIS) aimed at identifying the vulnerability of the cultural heritage in Italy (Baldi et al. 1987). The inspection protocol includes the survey of a number of relevant archeological and architectural assets using different levels of refinement. The protocol is based on the same structural breakdown as in CICD. For each element, the inspector recognizes the presence of damage. Any damage seen is specified by class, type, extension (percent of the damaged surface over the total) and urgency of action. Damage is classified in a lexicon of 57 different types aggregated in six classes, namely: structural, desegregation of materials, humidity, biological attack, alteration of surface layers, missing parts.

### 2.2 *Software implementation*

The prototype system under development is completely based on the Internet, through a user friendly web interface (Fig. 1). Once logged in, the user is transferred to the front page, which carries news on the system release. From the same page, users can download procedures, in the form of *pdf* documents. Using the main menu, the user can browse the various site sections, including: *Inventory*, *Inspections*, *Monitoring*.

The *Inventory* section represents the most direct way to navigate the building heritage. The main page includes a basic search engine, a result list including the relevant characteristics of the building, and a multi-tab window showing information on the selected building. Inventory data comprises a great part of the CICD records, as well as multimedia attachments, such as images, documents, FEM models, AutoCAD files.

In the *Inspections* section, inspectors can record the data resulting from a condition assessment. In detail, the inspector assigns to each damaged element a list of alterations, specifying type and extension. When appropriate, he is also required to detail his evaluation with a summary verbal description accompanied by digital images.

### 2.3 *Integration with monitoring systems*

Traditionally, risk evaluation is based on visual inspection, using heuristic models. HHMS intends, on one hand, to integrate visual inspection data with monitoring data and, on the other, to use risk evaluation methods based on probability. This system is currently based on visual inspection, but we expect to replace it gradually with an instrumented monitoring concept, as soon as technology will make available sufficiently low cost instruments. At the time of writing, the data acquisition and risk analysis section are still under development. This part of the system includes a separate database, and data analysis models. All instrumental data acquired from a specific building is directly stored in a separate database. Here too and as far as possible, we attempt to use existing database structures, such as that proposed by Inaudi et al. (2002). Raw and preprocessed data can be retrieved and represented graphically using the web application, within the *Monitoring* section.

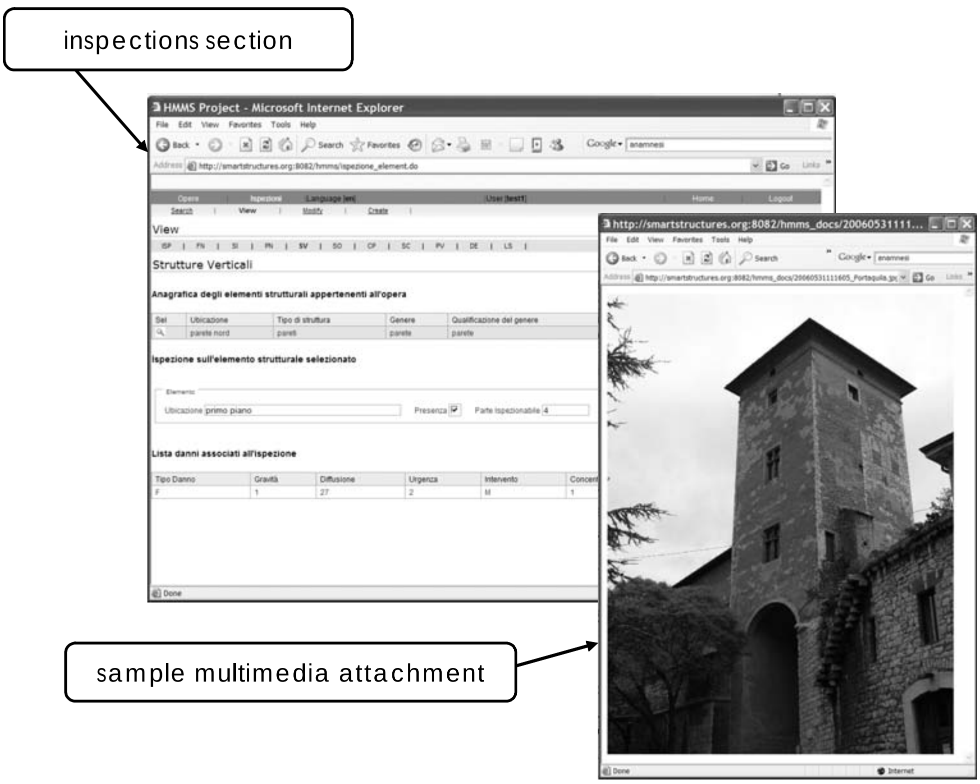


Figure 1 : Display of the HHMS web interface.

## 3 CASE STUDY DESCRIPTION

The case study chosen for the demonstration is the Aquila Gate in Trento (Castelnuovo 1987). This monument is a 31 m high Tower which is part of the 13th century walls of the city of Trento. Originally, it was a simple defense tower above a gate to the city. At the end of the 14th century, the tower was radically altered and joined to the Buonconsiglio Castle, the seat of the Prince-Bishop of Trento. What makes this monument unique, and worthy of attention, is the fresco *Cycle of the Months*, decorating the room on the second floor, considered one of most important International Gothic works in Europe.

As shown in Fig. 2, the tower features at ground level a passage covered by a barrel vault while at the upper level the plan is rectangular, 7.8 m by 9.0 m. The building as a whole is almost symmetrical; however, it is asymmetrically connected to the city wall and to the adjacent buildings; and this clearly influences its structural response. The masonry structure is also not homogeneous, and shows clear traces of its construction process. The ancient defense tower can still be recognized to the east or outside of the gate: the plan is C-shaped, 7.8 m by 4.5 m and the height is 25.6 m. The 14th century enlargement closes the tower to the west and raised the gate by an additional storey. An endoscopic test campaign showed that these two parts of the masonry body have completely different stratigraphy and mechanical properties. In detail, the lower level walls are 40 cm thick and of stone blocks, with an incoherent wall filling. At the upper levels, the older portion of masonry is built of thick stone blocks, while the most recent one is brick and blocks of varying sizes. The two portions of masonry seem to be structurally disconnected: one objective of the monitoring system is to analyze the effectiveness of the joint between the parts.

Based on the dimensions and the results of endoscopy, we developed a 3-Dimensional Finite Element Model (FEM, Fig. 3) to predict the tower response to various load and environmental scenarios. So far, the mechanical properties of walls and fillings are assigned based on values found in the literature. We expect to calibrate these values to fit experimental data, as soon as monitoring will be active.

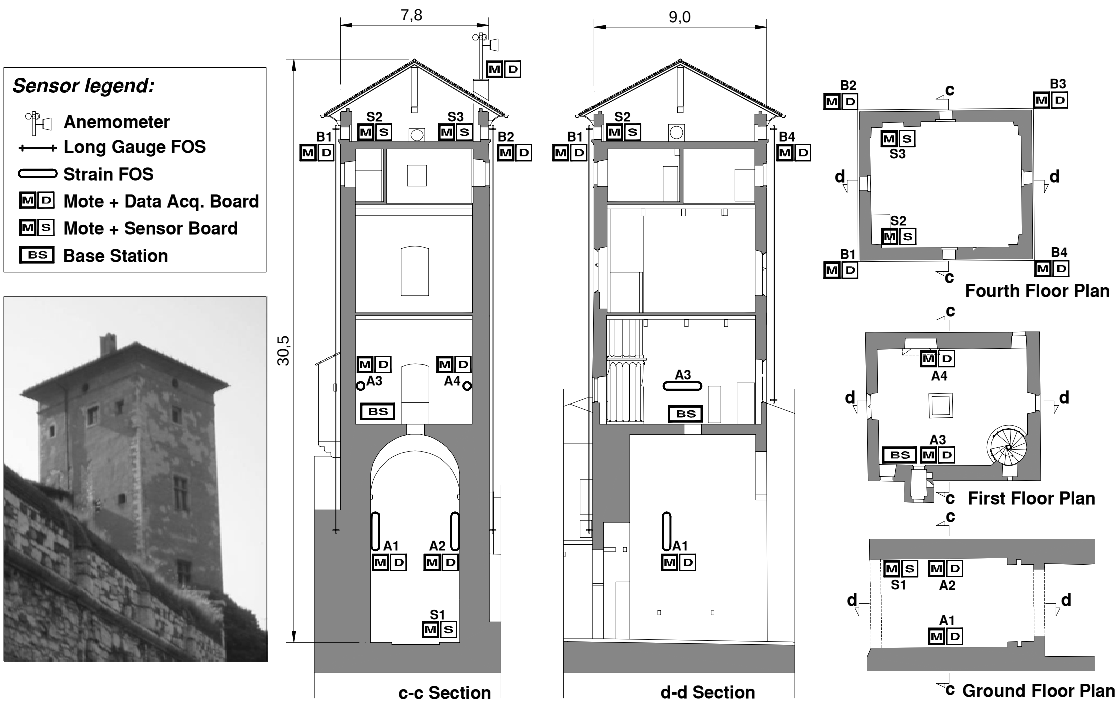


Figure 2 : Overview of the Tower; plan view and cross sections showing the instruments to be installed.

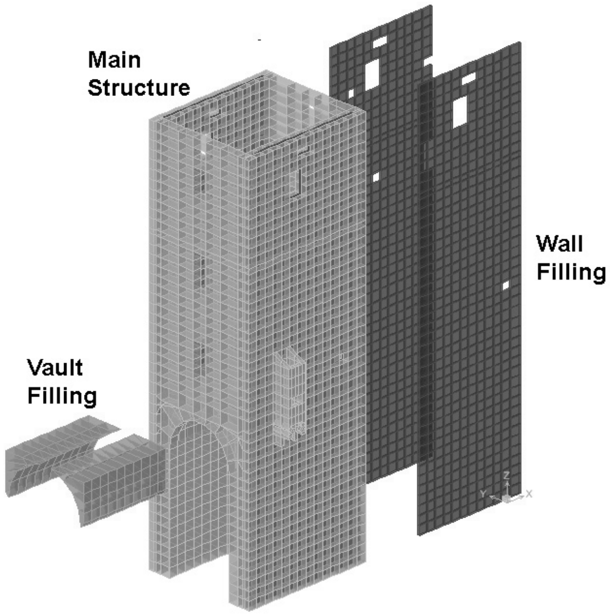


Figure 3 : FEM model of the Tower.

## 4 OVERVIEW OF THE MONITORING SYSTEM

Network sensors of the Mote type are the basis of the monitoring system. Mote technology, sometime referred to as Smart Dust, was originally developed at the University of California, Berkeley (Kahn et al. 1999) and is currently commercialized by Crossbow (http://www.xbow.com). In essence, Motes are small-scale devices integrating one or more transducers, a data acquisition system, computing capacity, a two-way radio and a power supply. What makes Motes interesting to researchers is their expected future millimeter dimension and low cost, all features that will make them suitable for intensive distributed applications. Recently, this technology has met increasing success in civil and earthquake engineering, as reported, for example, in Wong et al. (2005). See also Lynch and Loh (2006) for a state-of-the-art review of wireless sensor applications.

The structural monitoring of the Aquila Tower is primarily driven by the need to preserve its paintings. Sensors include accelerometers, thermometers and strain gauges. We select sensing techniques with a view to their integration into the Mote platform. Special attention is also paid to their long-term durability, and for this reason the installation will include prototypes of new fiber-optics gauges, along with traditional electric gauges. Sensors are arranged to record both structural response and external effects (such as wind, road traffic vibration, temperature change), in order to real-time calibrate the model parameters and to identify any possible occurrence of anomalous situations. External effects are recorded by an anemometer, located at the roof, a triaxial base ground accelerometer (labeled S1 in Fig. 2), plus a number of thermometers and humidity sensors. The vibrational response is acquired by a set of accelerometers (S2 and S3) located at the top floor, while local strain is recorded on the ground floor (A1 and A2) and on the first floor (A3 and A4) using an innovative type of long gauge-length FOSs. Another FOS model is used to detect vertical elongation at the four corners the tower (B1 to B4).

Particular attention is paid to measurements as related to the state of the frescos. Cracking of the frescos could be related to excessive local strain or strain-vibration, but applying sensors directly to the frescos is clearly unacceptable. For this reason, the strain field needed for assessing the state of the frescos can easily be extrapolated using the FEM on the basis of the measures recorded at the points actually instrumented.

Using the same FEM, it is possible to simulate the response of the installed sensors to different load and damage scenarios. For instance, Table 1 reports the expected measurements at four sensors for a number of effects, including subsidence, thermal gradients, wind and snow. Although these values have been obtained using a non-calibrated model, they let us understand the sensitivity of the measurements under the various scenarios. As an example, it is interesting to note that thermal gradients cause the maximum absolute strains, but only a minor component of this is stress-induced. Because damage to the frescos is mostly related to stress-induced strain, this fact underlines the need for the system to distinguish elastic effects from temperature effects.

Table 1 : Displacements and strain response for various load and distortion scenarios.

| | Strain A1 [με] | Strain A2 [με] | Strain A3 [με] | Displ. B1 [mm] |
|---|---|---|---|---|
| 5 mm subsidence scenario | 106 | -99 | 58 | -3.65 |
| Thermal distortion on a summer day (total) | 262 | 174 | 2.0 | 4.3 |
| Thermal distortion on a summer day (elastic) | 20 | 10 | - | - |
| Thermal distortion on a winter day (total) | -186 | -203 | - | -5.5 |
| Thermal distortion on a winter day (elastic) | -14 | -15 | - | - |
| 50-year return period wind from west | 1.9 | 1.9 | - | -0.13 |
| 200-year return period snow | -1.1 | -0.8 | - | 0.02 |

## 5 IDENTIFICATION PROCEDURE

More generally, the identification process tries to recognize symptoms of a specific scenario from a set of measurements, in a Bayesian statistical framework. This approach provides not only a diagnosis of potential structural damage, but also a direct assessment of its accuracy (Sivia 1996). A mutually exclusive and exhaustive set of $Nd$ scenarios ($S_1,S_2,\ldots,S_{Nd}$) is assumed. The monitoring system makes use of $Ns$ sensors, labeled ($s_1,s_2,\ldots,s_{Ns}$), each providing measures for each of $Nt$ time values ($t_1,t_2,\ldots,t_{Nt}$). $M_{k,j}$ identifies the measure obtained from sensor $s_j$ in time $t_k$, and $\{M_{k,j}\}$ indicates the whole set of measures, for every sensor and time value. For each scenario, Bayes' theorem allows calculation of posterior probability from prior probability, likelihood and total probability, using the following general expression:

$$\mathrm{prob}\left(S_n \left|\left\{M_{k,j}\right\}, I\right.\right) = \frac{\mathrm{prob}\left(\left\{M_{k,j}\right\}\left|S_n, I\right.\right)\cdot \mathrm{prob}\left(S_n \left|I\right.\right)}{\mathrm{prob}\left(\left\{M_{k,j}\right\}\left|I\right.\right)} \tag{1}$$

where $I$ indicates all the background information. Prior probabilities prob($S_n|I$) derive from external knowledge, independent of the monitoring system. A damage scenario is described by a random parameter vector ${}^n\mathbf{x}$, with probability density function ${}^np_x({}^n\mathbf{x})$, and a theoretical model which predicts the structural response. This model can be formally represented by a function ${}^nr_j({}^n\mathbf{x},t_k)$, which provides the structural response at position $s_j$, at time $t_k$, in scenario $S_n$ for a specific value of ${}^n\mathbf{x}$. The prediction error ${}^{n,x}e_{k,j}$ is the difference between the actual measure and the predicted response for scenario $S_n$ and parameter vector ${}^n\mathbf{x}$. This error depends on instrumental noise as well as on other unpredictable factors. We can assume that the distribution $p_e$ of the prediction error independent of $S_n$ and ${}^n\mathbf{x}$, and that different prediction errors are mutually uncorrelated. Under these assumptions, we obtain:

$$\mathrm{prob}\left(\left\{{}^{n,\mathbf{x}}e_{k,j}\right\}\right) = \prod_{k,j} p_e\left({}^{n,\mathbf{x}}e_{k,j}\right) = \prod_{k,j} p_e\left(M_{k,j} - {}^nr_j\left({}^n\mathbf{x},t_k\right)\right) \tag{2}$$

The likelihood for scenario $S_n$ can be calculated integrating over the whole parameter domain $D^n\mathbf{x}$, using ${}^np_x$ as a weighting function:

$$\mathrm{prob}\left(\left\{M_{k,j}\right\}\left|S_n, I\right.\right) = \int_{D^n\mathbf{x}} {}^np_x\left({}^n\mathbf{x}\right)\cdot \prod_{k,j} p_e\left(M_{k,j} - {}^nr_j\left({}^n\mathbf{x},t_k\right)\right)\cdot d\,{}^n\mathbf{x} \tag{3}$$

This integration could be very time and resource consuming. Beck and Katafygiotis (1998) proposed an asymptotic approximation of equation (3), and more recently Beck and Au (2002) developed a procedure to apply Monte Carlo algorithms to this task. Whatever method is used for estimating the right hand side of equation (3), posterior probability can be derived by using Bayes' theorem (1), where:

$$\mathrm{prob}\left(\left\{M_{k,j}\right\}\middle|I\right)=\sum_{m=1}^{Nd}\left[\mathrm{prob}\left(\left\{M_{k,j}\right\}\middle|S_m,I\right)\cdot\mathrm{prob}\left(S_m\middle|I\right)\right] \tag{4}$$

In summary, this procedure assigns a probability of occurrence to each allowable scenario, given the set of measurements $\{M_{k,j}\}$ acquired through the monitoring system.

To better understand how this procedure works, let us consider the case where only two scenarios, $S_1$ and $S_2$ are allowed. $S_1$ simulates a situation where *nothing occurs*: the ideal structural response is a constant zero and actual measurements depart from zero only due to error. Conversely, $S_2$ simulates a subsidence at the north side of the foundation. Let us further assume that only strain sensors $s_1$ and $s_2$ (corresponding to strain-gauges A1 and A2 of Fig. 2) are recording. Also, a total prior ignorance is assumed, so that prob($S_1|I$) = prob($S_2|I$) = 0.5. For $S_1$, no parameter is involved in the ideal response and ${}^1r_j({}^1\mathbf{x},t_k) = 0$, therefore equation (3) reduces to:

$$\mathrm{prob}\left(\left\{M_{k,j}\right\}\middle|S_1,I\right)=\prod_{k,j}p_e\left(M_{k,j}\right)\cdot\int_{Dx}{}^1p_x\left({}^1x\right)\cdot d\,{}^1x=\prod_{k,j}p_e\left(M_{k,j}\right) \tag{5}$$

As for $S_2$, the effect of a subsidence is simulated assigning to the north foundation a uniform vertical displacement $\delta(t) = \delta_{inf}\,(1\text{-}e^{-\lambda t})$, where $\delta_{inf}$ is the asymptotic value for the subsidence, and $\lambda$ controls the subsidence velocity. In this case the parameter vector reads ${}^2\mathbf{x} = [\delta_{inf}\ \lambda]$. Sensors response to a subsidence can be simulated using the FEM, obtaining: ${}^2r_1(t)$= 21.32 $10^{-3}$ $m^{-1}$ $\delta(t)$; ${}^2r_2(t)$= -19.80e-3 $m^{-1}\cdot\delta(t)$. Parameter distributions are defined by two independent Gaussian distributions: pdf($\delta_{inf}$)=Norm($\mu_\delta,\sigma_\delta$), pdf($\lambda$)=Norm($\mu_\lambda,\sigma_\lambda$), with $\mu_\delta$ = 1 mm, $\sigma_\delta$ = 0.2 mm, $\mu_\lambda$ = 0.6 days$^{-1}$, $\sigma_\lambda$ = 0.2 days$^{-1}$. The distribution of the prediction error $p_e$ is assumed to be a zero mean Gaussian with $\sigma_e$ = 20 με.

Given a set of measurements $\{M_{k,j}\}$, probability prob($S_1|\{M_{k,j}\},I$) and prob($S_2|\{M_{k,j}\},I$) can be computed. Fig. 4 reports an example of simulated measurements for scenario $S_2$. In detail, dotted lines represent the simulated response of the two sensors, while the continuous lines represent the ideal responses for scenario $S_2$ when parameters $\delta_{inf}$ and $\lambda$ are deterministically assumed equal to their mean values. In the same graph, the baseline represents the ideal response of both instruments in scenario $S_1$. The identification process applied to these data assigns posterior probabilities of 26.6% and 73.4% to $S_1$.and $S_2$, respectively.

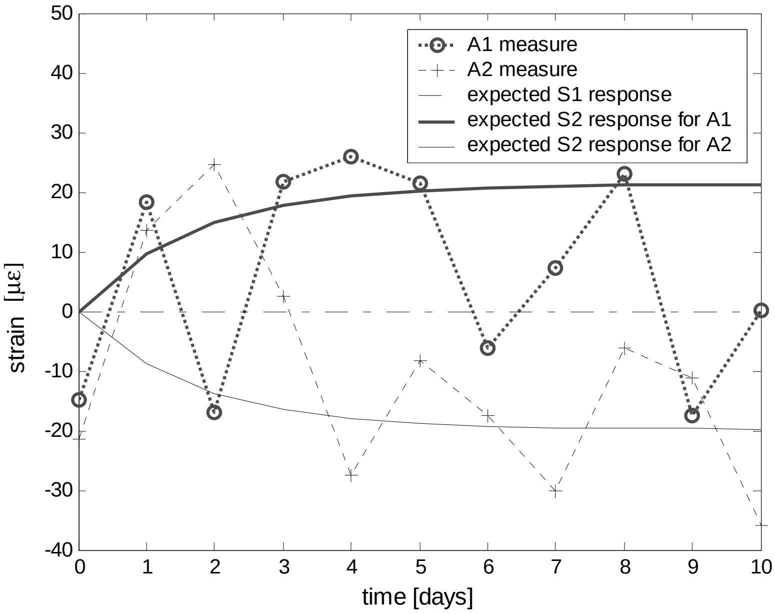


Figure 4 : Simulated measurements during subsidence, for sensors A1 and A2.

## 6 CONCLUSIONS

In this paper we present the outline of a developing framework for the real-time status monitoring and risk assessment of historic buildings. This framework is based on the so-called Historical Heritage Management System, an Internet based platform capable of collecting and managing data from both from visual inspection and on-line monitoring systems. The success of this approach requires exploitation of low-cost distributed sensing technology and development of suitable statistical algorithms to process the large amount of data collected.

The proposed identification procedure provides a rational quantification of the influence of monitoring data on the knowledge of the occurrence of different scenarios. In a broad sense, the framework application is twofold. Before installing the monitoring system, it can serve as an instrument to predict the effectiveness of alternative setups, by correlating type, number, accuracy and position of instruments to their ability to detect different types of damage. After installation, it provides a useful interpretation of the measurements, offering not only a diagnosis of structural damage, but also a direct assessment of its accuracy. The effectiveness of this procedure has been illustrated with a basic example. Although this example is extremely simplified, the general approach can be extended to a broader class of problems, and might include manifold scenarios, model or material uncertainties, as well as prior knowledge of parameter distribution.

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