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MANAGING THE HISTORICAL HERITAGE USING DISTRIBUTED TECHNOLOGIES

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In this article we outline a research effort aiming to develop technological tools for real-time risk management of historic buildings. In detail, the project includes 1) the development of a prototype Historical Heritage Management System (HHMS), with 2) the technological and conceptual tools for integrating this HHMS with real-time monitoring, and 3) the demonstrative application of a pilot monitoring system, working within this framework, to a case study, the Aquila Gate in Trento. Motes network sensors are the basis of the monitoring system. We show that the risk-updating methodology proposed is able to deal with all the uncertainties involved (measurement noise, model uncertainty, inaccurate prior information) and to early-warn the manager of any possible future failure condition.

KEY WORDS: management system, cataloguing, risk analysis, decision-making, Bayesian update, fiber optic sensors, Motes

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. A rational and quantitative evaluation process typically includes these steps: information acquisition, data processing, numerical modeling, evaluation of potential scenarios, risk analysis, decision-making. Often, each stage will develop independently of the others and at different times; thus 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 timescale between the first experimental data acquisition and final evaluation is in months or years. While this time span is tolerable when we are dealing with slowly progressing diseases, this is not acceptable when the first appearance of anomalies is shortly followed by irreversible damage. In this case an early recognition of these signs is of crucial importance for timely action on the structure.

It is the authors’ opinion that the technologies now under development can turn the previously mentioned process into an almost real-time operation. We are seeing rapid development of sensor technology that will radically change monitoring methods for civil structures in coming years. Fiber optics technology offers today durable solutions, and recent advances in micro-opto electro-mechanical systems (MOEMS) suggest that in the near future we will be able to rely on very small-scale mechanical and optical devices. Wireless communication too can simplify many installation and
operation issues. We also expect these technologies to be available at very low cost. The idea is to take advantage of low-cost distributed sensor networks to permanently monitor historic buildings and to use Internet-based analysis tools to deliver real-time risk information to those entrusted with the preservation of our heritage.

Permanent monitoring systems have found in the past decade widespread application in all fields of structural engineering, including the preservation of the historic heritage. Based on the cases reported in technical literature, we may have the impression that today the approach to monitoring is strictly problem dependent: deciding whether to instrument, what type of instrumentation is needed, and how to interpret the data recorded all seem to be technical issues left to the judgment of the engineer in charge of the evaluation. In reality the decision about any intervention should be a matter for the owner or for those responsible for the preservation of the building (typically local conservation agencies): in decision-making, a conservation agency must carefully evaluate the benefit of undertaking an action, keeping in mind issues that often go beyond the merely structural aspect, such as the historical, architectural or symbolic value of the building or the socioeconomic impact of the action. In addition, budget limitations require actions to be ranked, with priority for cases that carry more risk and preference for actions that are more effective in economic terms: in other words, the management of the historic heritage operates at the network level, rather than at the single building level. As the quantity and variety of information involved grows, appropriate technical tools are needed to convert this mass of data into risk indices and intervention priorities.

In this article, we outline a research effort aiming to set up a prototype of a management system implementing the aforementioned paradigm in a consistent framework based on risk analysis and widespread use of instrumental monitoring. More in detail, the project includes: 1) the development of a prototype Historical Heritage Management Systems (HHMS), with 2) the technological and conceptual instruments for integrating this HHMS with real-time monitoring, and 3) the demonstrative application of a pilot monitoring system, working within this framework, to a case study. HHMS is a prototype online database with Internet-based instruments for inventory, conservation state assessment, risk evaluation, and prioritization of action. The basic components of HHMS are described in detail in Section 2. The system can automatically record, process, and analyze data flows from permanent monitoring systems. Possibly the most challenging aspect of the management concept is to combine real-time monitoring, data processing, risk analysis and decision making, within the same framework. System operation requires techniques for processing the large amount of data acquired by the monitoring system to develop information on the risk of the structure. The general method used for identifying damage is based on Bayes’ principle, as described in detail in Section 3.

The case study chosen for the demonstration is the Aquila Gate, one of the most important historical monuments in the Italian Province of Trento. In Section 4, a description of this building is given, with information on the monitoring system installed and the risk analysis procedure. 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, including both fiber optics and electrical gauges. Finally, some conclusive remarks are provided at the end of the article.
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 information needed to make decisions for the conservation of the architectural heritage that 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. Numerous examples of BMS can be found in the literature (e.g., Frangopol et al. (2007), Thompson et al. (1998), Woodward (2002), and also Zonta et al. (2007b)). 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 difference, 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. Figure 1 shows the layout of the management system developed. In detail, the system operates based on the information stored in a database, today physically located in a single server, but that can be split up over different machines, when the complexity of the information requires a more sophisticated layout. The data includes: inventory data (core data and structural decomposition into elementary units), condition information, and instrumental monitoring records. Information input to the database is partly manual, for the inventory and the results of visual inspection, and partly automatic for data from instrumental monitoring. Manual input is based on procedures compatible with standards developed by the Istituto Centrale per il Catalogo e la Documentazione (ICCD [Central Institute for Catalog and Documentation]) and by the Istituto Centrale per il Restauro (ICR [Central Institute for Restoration]), as better specified in Sections 2.1 and 2.2, respectively, whereas Section 2.3 explains the integration of HHMS with monitoring data. All the information collected in the database is processed by deterioration, risk and structural models, and converted to risk data, as explained in detail in Section 3.

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 homogeneously by the system, to gain statistical information on the state of conservation and vulnerability of the entire heritage. In defining the inventory system, we attempted to apply, as far as possible, existing inventory systems, codes, and standards. Basically most countries have developed in the past standards for the documentation of the cultural heritage, including architectural items (e.g., these websites: the French Direction de l’Architecture et du Patrimoine; the Dutch Rijksdienst voor Archeologie, Cultuurlandschap en Monumenten (RACM, 2008); the Norwegian Directorate for Cultural Heritage (Riksantikvaren, 2008); the Portuguese Instituto Português do Patrimônio Arquitectónico (IPPAR), and the Irish National Inventory of Architectural Heritage (NIAH); also Grant, 1994;
de Massary and Coste, 2007). An exhaustive review of architectural cataloguing standards in Europe can be found in Porfyriou (2002).

At the same time, a significant effort has been put into defining commonly recognized standards at the international level. Possibly the most successful effort of this type is that undertaken by the International Committee for Documentation of the International Council of Museum Documentation (ICOM-CIDOC, 2008), resulting in

Figure 1. Logical layout of the Historical Heritage Management System (HHMS). ICCD, Istituto Centrale per il Catalogo e la Documentazione; ICR, Istituto Centrale per il Restauro (figure is provided in color online).
the inventory standard *Core Data Index to Historic Buildings and Monuments of the Architectural Heritage* (Thornes and Bold, 1998). Rather than proposing an exhaustive set of data, the standard recommends the common use of a relatively limited set of data elements (the so-called Core Data), strictly necessary to allow minimum mutual interrogation and exchange between different national systems.

In our case, most of our database structure was taken from the cataloguing Standard issued by the ICCD of the Italian Ministry of Cultural Heritage and Activities (ICCD, 2008). The programmatic objective of ICCD is to develop methods and standards for selection and description of our cultural heritage, aimed at creating a general inventory. The standards developed by ICCD define the data structure and the set of inventory rules for all types of cultural items, not limited to historic architecture, but also including movable items, archaeological sites and monuments. As for historic buildings, the data includes ownership information, location, history, previous restoration information, (which are essentially compatible with the CIDOC Core Data) plus a structural description of the building itself. The conceptual approach is to break down the building into a number of structural elements that 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 or mosaics).

### 2.2. Visual Appraisal of the Condition

As for the assessment of the conservation state, we adopted an inspection protocol compatible with that developed by the ICR within the risk map project (ICR, 2008). As seen in the ICR website, the ICR Risk Map is an evolving geographic information system aimed at identifying the vulnerability of the cultural heritage in Italy (Baldi et al., 1987; ICR, 1997). The inspection protocol includes the survey of a number of relevant archaeological and architectural assets using various levels of refinement. The protocol is based on the same structural breakdown as for the ICCD. 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) severity, and urgency of action. Damage is classified in a lexicon of 57 different types aggregated in six classes, namely: 1) structural, 2) degradation of materials, 3) humidity, 4) biological attack, 5) alteration of surface layers, and 6) missing parts. As for the severity, the damage is classified in a scale of 5, from light to ultimate: the evaluator ranks damage on the basis of the verbal description suggested in the inspection procedure. The scheme of Figure 2 illustrates an example of damage classification as applied to element *vertical structure*, of type *masonry wall*. The example assumes a damage of class A, *structural*, type #3, *diagonal cracking between two openings*; in this case the damage severity is defined on the basis of the maximum crack width \( w \): damage is light if \( w < 2 \) mm, and similarly for the remaining severity levels. In a similar way, the inspector is required to specify the *urgency of action* in a scale of 5; for which urgency level 1 means *no progression* and level 5 indicates *rapid progression of damage* . . . *action urgently needed in order to prevent irreversible loss of the element.*
2.3. Integration with Monitoring Systems

The most interesting feature of the system is that all manual data input, currently based on visual inspection, could theoretically be replaced with an instrumented monitoring system, as soon as technology will make available sufficiently low-cost instruments. 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 attempted to refer to existing database structures. The methodology adopted in HHMS distinguishes static data from dynamic data. Static data is recorded with a scan rate lower than one sample per minute: in this case, the approach is to save all the data, with no compression, using the database standard proposed by Inaudi et al. (2002). This approach is not feasible when dealing with dynamic data flows, due to data storage limitation. This is the case, for example, of a continuous data flow from accelerometers, where the scan rate required is typically in the order of 200 Hz. In this case the approach is to maintain in the database the full set of recent signals, and to extract from the older records only the features that are significant for further analyses (for example: spectral components, minimum, maximum or mean values). The features extracted are then treated by the system in the same way as static data.

2.4. Software Implementation

Many examples of multimedia applications for documenting the historical heritage are found in the literature: Ausserer et al. (2003) reports a number of interesting experiences, but see also Romão et al. (2006).

The prototype of HHMS developed is completely based on the Internet, through a user-friendly web interface (Figure 3). 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 ICCD records, as well as multimedia attachments, such as images, documents, finite element models (FEMs), 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, the inspector is also required to detail the evaluation with a summary verbal description accompanied by digital images. Raw and pre-processed data can be retrieved and represented graphically using the web-based application, within the **Monitoring** section.

### 3. MANAGEMENT AND DECISION MAKING TOOLS

#### 3.1. Decision-Making Principle

In a traditional management system, prioritization and risk ranking are based on visual inspection, using heuristic models. In HHMS, the need to integrate
consistently data of differing types requires the application of risk evaluation methods based on well-founded probabilistic principles. In detail, the prioritization approach proposed is based on the following principle: priority is given to those actions that, given a certain budget, will minimize the risk of an unacceptable event \( X \) in the whole network over a specific time span \( t_L \). Recast in a quantitative format, the decision-making process reduces to the association of a priority index \( \alpha \) to each of the potential actions (further assessment, repair, retrofit) as well as to any specific maintenance scenario. A priority index \( \alpha \) is expressed by:

\[
\alpha = \frac{\text{prob}(X) - \text{prob}(X|a)}{\Delta C}
\]

where \( \text{prob}(X) \), below called risk, is the cumulative-time probability of an unacceptable event \( X \) in the stock over the time span \((0,t_L)\), \( a \) is the action considered (e.g., restoration) and \( \Delta C \) is the economic cost associated with the action (e.g., the repair cost). The evaluation of the cost of an intervention \( \Delta C \) does not need further explanation, while the calculation of risk \( \text{prob}(X) \) deserves here much more consideration.

A first major issue for the practical application of the decision principle is the definition of unacceptable event: it should be clarified that this concept is not merely technical, but involves careful evaluation of the social impact of the potential event. In the mind of a structural engineer, a structural failure is typically seen as an unacceptable event; however, the owner’s attention is mainly focused on the consequences of a failure, in terms of public safety or irreversible loss of to the heritage. In a broad sense, the complete collapse of a building and the mere cracking of a stone architrave are both structural failures, but evidently a conservancy will pay much more attention to the former rather than to the latter. More generally, to define what is an unacceptable event is an issue that concerns the conservation agency, and reflects its management policy. In the current version of HHMS, we defined as unacceptable the following events:

- Structural failures that jeopardize public safety; and
- Condition state causing an irreversible loss of an object of artistic, historical, or cultural relevance, or of part of it.

Another point is the selection of the time span \( t_L \): this is to be chosen having in mind the objective of the analysis. When the aim of the evaluation is to rank interventions by their urgency, the view of the decision-maker is a short-term one, and in this case \( t_L \) should be of the order of a few years. Conversely, when the problem is to define a long-term strategic plan for intervention, a time span of the order of \( t_L = 50 \) years seems more appropriate.

The practical numerical method for calculating risk then changes on the basis of the information available. For risk associated with apparent damage, as found during visual inspection, HHMS uses the simplified model described in the next Section 3.2. When the instrumental data is available, a more sophisticated algorithm allows for updating risk in real-time, as described in Section 3.3.

### 3.2. Risk Analysis Based on Apparent Damage

HHMS evaluates risk in a future time span considering that the disease might progress in time. In the case of apparent damage states, this requires definition of a
deterioration model. In HHMS, the deterioration model applies to each source of risk seen in the building during visual inspection. The present or future degradation state is statistically defined by a state vector $s$, collecting the probabilities of the element being in 1 of the 5 possible ICR levels of severity introduced in Section 2.2. Such a damage model, based on a discrete number of possible states, suggests use of a classic degradation model of Markovian type, similar to that used, for example, in Thompson et al. (1998) to predict deterioration in bridge elements. A Markovian model involves definition of the transition probabilities from one state to another more severe. In detail, let us define $d_{ij}$ the probability of moving into state $i$ at year $t_0 + 1$ given that at the current year $t_0$ the element is in state $j$. These transition probabilities depend on the type of damage, vulnerability factor and urgency index assessed during the inspection.

In the most general form, there will be 5 times 5 values of transition probabilities between all possible severity condition pairs, which can be ordered to form a 5 by 5 transition matrix $D$. The time-variant vector of state $s$ changes after $t$ years according to:

$$s(t + t_0) = D^t s(t_0)$$

In the model adopted, element $d_{55}$ is assumed equal to $1 - d_X$, where $d_X$ is the probability of an element damaged in its more severe condition to cause an unacceptable event in the next year. Based on this definition, the cumulative time risk associated with a damaged state can be estimated using

$$\text{prob}(X) = d_X \sum_{t=1}^{t_1} D^t s(0)$$

where $d_X = [0 0 0 0 d_X]$. Under some special circumstances, an additional damage state labeled 0, is introduced, meaning that the possibility of having the element damaged in the future is considered, even if at present there is no evidence of damage.

### 3.3. Risk Analysis Based on Recorded Data

The simple approach presented previously is appropriate when the damage progression rate can be checked by routine inspection. When the source of information is the data recorded by the monitoring system, a major issue is how to exploit appropriately the large amount of data recorded by the sensors. The general paradigm of the method here presented is to try recognizing real-time symptoms of a specific hazardous scenario $S_n$ (e.g., leaning in progression, incipient crushing of material, critical vibration level), from a set of instrumental measurements $M$, using the principle of Bayesian statistical analysis. Bayesian theory of probability originates from Bayes’ well-known essay (Bayes, 1763). Reference works on the subject are those by Jaynes (2003) and Skilling (1998) while many modern specialized textbooks provide the reader with a critical review and applications of this theory to data analysis (e.g., Gregory, 2005; Sivia, 2006). Of all the articles dealing with application of Bayesian theory to civil problems, we wish to mention the work by Beck’s group (Beck and Katafygiotis, 1998; Beck and Au, 2002; Papadimitriou et al., 1997) and by Sohn and Law (1997; 2000).
Say 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 in time $t_k$ from sensor $s_j$, and $M_k$ indicates the set of measures provided by all sensors during a time range, which spans from $t_1$ up to $t_k$. We assume that the appearance of damage in the structure will somehow modify the response history; the recognition method seeks to detect the presence of damage by comparison of the compensated measurements with the theoretical response produced by a model, for example a FEM.

In practice, it is convenient to divide the domain of the possible structural response into a mutually exclusive and exhaustive set of scenarios $(S_1, S_2, \ldots, S_{Nd})$, each defining the structural behavior in a specific condition. The structural response $r_{k,j}(\mathbf{p})$ for day $k$ and sensor $s_j$ in scenario $S_n$ is controlled by a certain number of parameters (e.g., activation time, progression speed), represented by vector $\mathbf{p}$. The structural response is completely defined by specifying a scenario and a value for the correlated parameter set. Here, as the Bayesian model selection theory (Gregory, 2005; Bretthorst, 1996), the discrete scenario can be seen as a meta-parameter which qualitatively identifies the type of response function (e.g., constant, linear, exponential) which in turn is specified by a parameter set.

Assuming scenario $S_n$ to be correct and after appropriate selection of the scenario’s parameter $\mathbf{p}$, the observational response can be expressed as:

$$m_{k,j} = r_{k,j}(\mathbf{p}) + e_{k,j}$$

where $e_{k,j}$ is an error that accounts both for the instrumental noise and for the unavoidable imprecision of the model assumed. Because from an epistemic point of view these uncertainties are random, $e_{k,j}$ is modeled as an uncorrelated zero-mean Gaussian noise. Its standard deviation $\sigma_j$ can be assumed independent of time, but generally changes with the sensor. Evidently $\sigma_j$ changes with sensor type, but we may also expect a dependency, for example, on sensor position or precision.

Once measures $M_k$ become available from the monitoring system, Bayes’ theorem allows calculation of the updated, or posterior, probability for each scenario $S_n$, from prior probability $\text{prob}(S_n)$, scenario likelihood $\text{PDF}(M_k|S_n)$ and evidence $\text{PDF}(M_k)$, using the following expression:

$$\text{prob}(S_n|M_k) = \frac{\text{PDF}(M_k|S_n) \cdot \text{prob}(S_n)}{\text{PDF}(M_k)}$$

where PDF denotes the probability density function of a random variable. Prior probabilities assigned to each scenario reflect the initial judgment of the evaluator, independently of the outcome of monitoring. On the contrary, likelihood computation requires detailed analysis of the predicted structural response in each specific scenario. First, the likelihood of a single sample $m_{k,j}$ can be expressed as function of the parameters $\mathbf{p}$ as:

$$\text{PDF}(m_{k,j}|\mathbf{p}, S_n) = \text{Normal}\left\{m_{k,j} - r_{k,j}(\mathbf{p}); 0, \sigma_j\right\}$$

where the notation $\text{Normal}\{x; \mu, \sigma\}$ indicates a normal distribution with mean value $\mu$ and standard deviation $\sigma$ calculated in $x$. As long as errors are assumed to be
uncorrelated for each time and sensor, the likelihood for the whole measure set $\mathbf{M}_k$ is obtained combining the likelihoods of all samples for all sensors and time intervals recorded:

$$\text{PDF}(\mathbf{M}_k|\mathbf{p}, S_n) = \prod_{j = 1, i = 1}^{N_t, i = k} \text{PDF}(m_{ij}|\mathbf{p}, S_n)$$  \hspace{1cm} (7)

Likelihood of scenario $S_n$ is then calculated by marginalization of parameters $\mathbf{p}$, i.e., by integrating parameter likelihood on the whole domain $D^p\mathbf{p}$, using their prior distribution PDF ($\mathbf{p}|S_n$) as weighting function:

$$\text{prob}(\mathbf{M}_k|S_n) = \int_{D^p\mathbf{p}} \text{PDF}(\mathbf{M}_k|\mathbf{p}, S_n) \cdot \text{PDF}(\mathbf{p}|S_n) \cdot d^p\mathbf{p}$$  \hspace{1cm} (8)

Solving Equation (8) could be very time and resource consuming. Beck and Katafygiotis (1998) proposed an asymptotic approximation, and more recently Beck and Au (2002) developed a procedure to apply Monte Carlo algorithms to this task.

As the scenario set is complete and mutually exclusive, evidence of measures $\mathbf{M}_k$ is simply obtained by summing on the scenarios:

$$\text{prob}(\mathbf{M}_k) = \sum_n \text{prob}(\mathbf{M}_k|S_n) \cdot \text{prob}(S_n)$$  \hspace{1cm} (9)

Once calculated the probability of being in a specific scenario using Equation (5), Bayes’ theorem also allows an estimate of the posterior distribution of the corresponding parameter $\mathbf{p}$, using:

$$\text{PDF}(\mathbf{p}|\mathbf{M}_k, S_n) = \frac{\text{PDF}(\mathbf{M}_k|\mathbf{p}, S_n) \cdot \text{PDF}(\mathbf{p}|S_n)}{\text{PDF}(\mathbf{M}_k|S_n)}$$  \hspace{1cm} (10)

Eventually, the posterior risk $\text{prob}(X)$, i.e. the probability that an unacceptable event $X$ is to be expected, is obtained averaging on all scenarios:

$$\text{prob}(X) = \sum_n \text{prob}(X|\mathbf{M}_k, S_n) \cdot \text{prob}(S_n|\mathbf{M}_k)$$  \hspace{1cm} (11)

where the risk conditional to a scenario $\text{prob}(X|S_n)$ is obtained solving the following integral:

$$\text{prob}(X|\mathbf{M}_k, S_n) = \int_{D^p\mathbf{p}} \text{prob}(X|\mathbf{p}, S_n) \cdot \text{PDF}(\mathbf{p}|\mathbf{M}_k, S_n) \cdot d^p\mathbf{p}$$  \hspace{1cm} (12)

In summary, given a fresh set of measurements $\mathbf{M}_k$, this procedure allows real-time updating of the probability of each scenario and of the risk associated, using Equations (5), (10) and (11).
4. DEMONSTRATIVE APPLICATION

4.1. Case Study Description and Preliminary Risk Analysis

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 (Figure 4). 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 Figure 5, 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 (Figure 6): 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 stratigraphic 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 building has been inventoried into HHMS and visually inspected according to the ICCD-ICR procedures described in Section 2. Table 1 summarizes the main points of the risk analysis. In practice, the apparent damage is limited to deterioration of few specific elements of the tower and the building does not present any serious

![Figure 4](image_url). Photographs of the overall view of the Aquila Gate, Trento, Italy: a) southwest, and b) east views (figure is provided in color online).
Figure 5. Plan views and cross sections of the Aquila Gate tower, Trento, Italy.

Figure 6. South elevation of the Aquila Gate: a) photograph, and b) scheme highlighting the ancient defense tower now incorporated in the new body (figure is provided in color online).
source of concern. The corresponding risk values, evaluated over a time span of 5 years, are almost negligible.

An additional source of concern, however, is the preservation of the frescos, in view of possible future tunneling work under the Buonconsiglio Castle area. The Castle is located on the edge of the historic center of Trento and in ancient times the Aquila Gate represented the main entrance to the city from the east. With the expansion of the city in the second half of the 19th century, most of the eastern city wall was demolished and the entrance to the city was moved a few hundred meters south of the original gate. Today this solution is inadequate for the increasing traffic demand. The solution to this problem, pursued by the Municipality of Trento, is to bypass the obstacle of the Buonconsiglio Castle with a road tunnel. Besides the cost of this solution, the tunnel has been long delayed due to concern by the conservancy that construction work might cause unwanted settlement of the castle foundations. As mentioned, the main source of concern is the delicate cycle of frescos hosted in the Aquila Gate. This is taken into account in HHMS by introducing a specific risk factor, under which in this case the risk does not refer to apparent but to potential damage. The timely estimation of the potential risk to the frescos requires real-time instrumental monitoring and appropriate response models to reproduce the structural behavior of the Tower, as described in detail in the next Section.

### 4.2. Overview of the Monitoring System and Finite Element Modeling

Apart from the specific problem highlighted in the risk analysis, the type and number of gauges actually installed in the Tower also respond to the demonstrative nature of the research project, where the pilot setup is seen as an opportunity to test the feasibility of new technologies for sensors and communication, which are now still in their infant stage.

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 Technology, Inc. (San Jose, CA). 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

<table>
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<tr>
<th>Element</th>
<th>Class and type</th>
<th>Severity</th>
<th>Urgency</th>
<th>Extension</th>
<th>prob(X)</th>
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</thead>
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<td>Wooden stair</td>
<td>E- Surface alteration</td>
<td>2</td>
<td>2</td>
<td>80%</td>
</tr>
<tr>
<td>SV</td>
<td>West masonry wall</td>
<td>A2- Cracking at the openings edge</td>
<td>1</td>
<td>2</td>
<td>30%</td>
</tr>
<tr>
<td>PV</td>
<td>3rd level floor</td>
<td>E- Surface alteration</td>
<td>1</td>
<td>3</td>
<td>10%</td>
</tr>
<tr>
<td>DEC</td>
<td>2nd level frescos</td>
<td>A1- Vertical cracking</td>
<td>0*</td>
<td>1</td>
<td>—</td>
</tr>
</tbody>
</table>

*Damage not apparent
example by Wong et al. (2005). See also Lynch and Loh (2006) for a state-of-the-art review of wireless sensor applications. In practice, a network sensor of the Mote type consists of a radio board coupled either to an integrated sensor board or to an analog-digital converter. Radio boards selected for this application are model MPR2400-MICAz, ZigBee compatible, with a nominal transmission speed of 250kbps, and a nominal outdoor range of 75 m. Power consumption is 1 mA in sleep mode and up to 14mA–20mA in transmission/receive mode. All technical detail can be found in the datasheet available at Crossbow website (available at: http://www.xbow.com [accessed January 27, 2008]).

Sensors installed include accelerometers, thermometers, and strain gauges, arranged to record both structural response and external effects (road traffic vibration, temperature change), in order to real-time calibrate the model parameters and to identify any possible occurrence of abnormal situations. External effects are recorded by a triaxial base ground accelerometer set (labeled A1 to A3 in Figure 5), plus a number of thermometers, physically mounted on the same sensor boards of the accelerometers. The vibration response is acquired by a set of accelerometers (A4 to A6) located at the top floor. Accelerometers and thermometers are all integrated onto off-the-shelf Crossbow sensor boards of type MTS320 (Figure 7). In these cases, we select the sensing solution primarily with a view to their integration into the Mote platform, even when the sensor specifications are not optimal for the application.

In the case of strain sensors, not available from Crossbow Technology, we decided to include prototypes of new fiber-optics gauges in view of their long-term stability and durability. The deformation across the joint is measured by a 0.6-m sensor located at the first floor (F2) using an innovative type of long gauge-length Fiber Optic Sensor (FOS), as shown in Figure 8. In detail the measurement principle is

![Figure 7. Photograph of a Mote network sensor (figure is provided in color online).](image-url)
based on the travel time of a light beam over a fiber optic coil pretensioned over the measuring base. As the sensor uses bare fiber and an extremely simple interrogation system, it is expected that the industrial deployment of this prototype may result in a very low-cost device.

Another FOS model, based on the same interrogation system, is used to detect vertical elongation at the southwest corner the Tower (F1), from level +5.7 m to level +26.8 m. In this case the measuring path is a protected optical fiber loop pretensioned between two metal anchorages (Figure 9). For both sensors the A/D conversion is carried out by a 12-bit MDA300CA Crossbow board, coupled to the MPR2400 radio board used by the other gauges. Additional radio boards (labeled with M in Figure 5) have been placed all over the Tower to serve as radio bridges where the transmission range between two nearby sensors is insufficient.

Figure 8. Photograph of an optical coil sensor (F2) installed across the southern joint (figure is provided in color online).

Figure 9. Very long gauge-length fiber optic sensor (F1) installed at the southwest corner: a) upper and b) lower anchorages (figure is provided in color online).
Particular attention was paid to measurements that relate to the state of the frescos. Cracking of the frescos could be caused by 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 a FEM on the basis of the measures recorded at the points actually instrumented.

Based on the dimensions and the results of endoscopies, we developed a three-dimensional FEM (Figure 10) to predict the tower response to various load and environmental conditions. Prior values for the mechanical properties of walls and fillings are assigned based on values found in the literature, then calibrated to fit the experimental observations of the monitoring system. A major point of uncertainty is still the degree of connection between the ancient and the most recent parts of the masonry: as one can easily imagine, the structural behavior of the tower changes significantly if we consider this connection effective or not. Inspection of the wall seems to show that the external leaves have no continuity across the joint; on the other hand, there is no apparent sign of cracking along the joint itself, as we would expect as a consequence of thermal expansion, and this suggest that the two parts might be somehow connected. The endoscopies and the first instrumental observation did not provide a final answer on this. To deal with this uncertainty, we decided to consider in the analysis two versions of finite element models, one (labeled Model A) having the two masonry parts fully collaborating, the other (labeled Model B) with the two parts completely disconnected.

Using the same FEM, it is possible to simulate the response of the installed sensors to different load and damage scenarios. For example, Table 2 reports the expected measurements at the two fiber-optic sensors (F1 and F2) and the corresponding horizontal strain $\varepsilon_f$ at the fresco surface, under a number of load conditions,
including subsidence, thermal gradients, wind and snow: these values 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 essentially related to stress-induced strain, this fact underlines the need for the system to distinguish elastic effects by appropriate temperature compensation.

4.3. Monitoring-Based Risk Update Algorithm

In the following we illustrate how the HHMS is set up for real-time risk estimation in view of the future tunneling work. In general the unacceptable event we want to prevent is cracking of the frescos: this situation might occur when the elastic strain at the fresco surface $e_f$ exceeds the limit tensile strain of the plaster $e_{ft}$. The limit strain is statistically assumed normal-distributed with mean value $e_{ff} = 150 \mu e$ and coefficient of variation of 20%. We can reasonably assume that only strain sensors F1 and F2 are sensitive to this type of distortion, and therefore only these will be considered in the risk updating procedure. For the sake of clarity in the following discussion, we will skip the matter of temperature compensation, although we note here that both the FE models and the identification procedure as applied to real life do consider the effect of temperature and other environmental factors: the full method implemented is as reported by Zonta et al. (2007a), to whom the interested reader is referred for more details.

To clarify how the real-time risk updating procedure works, let us consider that only two scenarios, $S_1$ and $S_2$ are allowed. Scenario $S_1$ simulates a situation in which nothing occurs: in this case, if we compensate the effect of external loads, the ideal structural response $^1r_{k,f}$ is constant and equal to zero at any sensor, and the actual measurements depart from the baseline only due to instrumental noise. Assume that no parameter is involved in this scenario, even if this is not the most general case.

Scenario $S_2$ simulates a differential foundation settlement at the southwest side of the Gate. The settlement model assigning to the south-west edge a

<table>
<thead>
<tr>
<th>Action</th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal distortion on a summer day (total)</td>
<td>+3872.69</td>
<td>+3700.58</td>
</tr>
<tr>
<td>Thermal distortion on a summer day (elastic)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Thermal distortion on a winter night (total)</td>
<td>-1733.32</td>
<td>-1729.64</td>
</tr>
<tr>
<td>Thermal distortion on a winter night (elastic)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>50-year return period wind from west</td>
<td>36.19</td>
<td>25.67</td>
</tr>
<tr>
<td>200-year return period snow</td>
<td>-24.90</td>
<td>-24.51</td>
</tr>
<tr>
<td>10-mm settlement at southwest foundation</td>
<td>+147.92</td>
<td>+72.94</td>
</tr>
</tbody>
</table>

Table 2. Expected structural response of the Aquila Gate, Trento, Italy, for various load and distortion scenarios

vertical displacement $\delta(t)$ varying with time according to the following exponential law:

$$
\delta(t) = \delta_\infty \cdot (1 - e^{-\lambda})
$$

(13)

where evidently $\delta_\infty$ defines the asymptotic value of the settlement and $\lambda$ is a parameter that controls the velocity of the phenomenon. In this case, the prediction of the structure response requires the aid of the FEM. As suggested in Table 2, the resulting structure response changes significantly, depending on the model selected. To deal with this uncertainty, a third discrete parameter $b$ is introduced, which can assume only two values, A or B, depending on the type of response assumed. Therefore, the parameter vector for $S_2$ can be formally written as $\mathbf{p} = [\delta_\infty \; \lambda \; b]$.

As mentioned previously, the Tower has never suffered any settlement, at least since the monitoring system has been in operation (since January 2007). Here we want to verify the ability of the algorithm to recognize early such a situation, as it may occur in the future, and to do this we must necessarily use simulated data. In this exercise, we generated an ideal response using model B, assuming for the settlement values of $\delta_\infty = 7\text{mm}$ and $\lambda = 0.04\text{day}^{-1}$, meaning that 90% of the settlement develops within 58 days. The response we ideally expect at the two sensors is that graphically represented in dash-dotted lines in the graphs of Figure 11, for a time span of 100 days. This ideal response is not exactly what we expect to get from the sensors in real life. For example during the day we experience thermal distortions (expansions or contraction); we can compensate the effect of temperature variation using the daily temperature history, but any unavoidable inaccuracy in the compensation model results in some noise. Then there is vibration of the structure caused by environmental effects (traffic, wind). And finally there is the instrumental noise. All these uncertainties result in practice in a noisy response. Based on the data acquired by the monitoring system to date, we can estimate the standard deviation of this noise as $\sigma_{\varepsilon,F1} = 30\mu\text{m}$ $\sigma_{\varepsilon,F2} = 15\mu\text{m}$, for sensor F1 and F2 respectively. Taking account of this noise, we can numerically simulate a realistic sampling of compensated measurements taken at the two sensors. The resulting signals are the daily samples plotted in the same Figure 11. Based on the qualitative observation of these signals, it is hard to understand whether there is settlement or not, especially if we limit our attention to the first few days of monitoring. Assuming that the limit tensile strain of plaster is equal to its mean value, i.e. $\varepsilon_f = 150\mu\varepsilon$, the FEM predicts that the first vertical cracking is expected to occur at time $t = 51\text{ day}$, for a settlement of $\delta = 6.09\text{mm}$.

We now want to verify if and how early the procedure illustrated in Section 3 lets us see the ongoing settlement. First we need to assign prior probabilities to each scenario and the corresponding parameters. Our initial view of the problem is that a subsidence during the construction of the tunnel is a very unlikely event (if not, the work will not even start), but that it cannot be excluded completely (if not, there was no concern and no need for the monitoring). We can numerically translate this judgment assigning to $S_2$ a prior probability $\text{prob}(S_2) = 1/1000$ and consequently to $S_1$ a prior probability $\text{prob}(S_1) = 0.999$.

Failing other information, we can assume that the prior distributions of parameters $\delta_\infty$ and $\lambda$ are both normal; appropriate mean values are $\mu_\delta = 10\text{mm}$ and $\mu_\lambda = 0.06\text{day}^{-1}$, which means that the settlement, if noticeable, is expected to be of the order of 1 cm and that it might develop in approximately 40 days. We recognize, however, that these assumptions are extremely uncertain: so coefficients of variation of 50% are
assumed a priori, corresponding to standard deviations of $\sigma_\delta = 5\text{mm}$ and $\sigma_\lambda = 0.03\text{day}^{-1}$, respectively. If the initial guesses were correct, the ideal responses of the sensors were those shown in dashed line in Figure 11, for Model A and Model B respectively. As mentioned, both of the models are virtually possible, though not equally likely. Comparison of the first signals acquired by the monitoring system with the prediction reported in Table 2, suggests that Model A (i.e., with the older and newer part effectively connected) is more likely than Model B. In numbers, we can assume prior probabilities $\text{prob}(A|S_2) = 75\%$ and $\text{prob}(B|S_2) = 25\%$, for the two models respectively. Given this information, Equation (11) shows that our initial perception of the risk of having a cracking of the frescos during the tunneling work is $\text{prob}(X) = 1.9 \times 10^{-4}$, as reported in Table 1, which is an extremely low value.

Figure 11. Simulated response at sensors F1 and F2 for settlement of the southwest foundation of the Aquila Gate tower, Trento, Italy.
As monitoring data is available, using Equation (5) we can update daily the probability of each scenario. Figure 12a describes how the probability $\text{prob}(S_2|M_k)$ of there being a settlement changes with time. The same graph also shows $\text{prob}(S_2,B|M_k)$, the probability of the structure responding according to Model B, while evidently the likelihood of Model A can be calculated as $\text{prob}(S_2,A|M_k) = \text{prob}(S_2|M_k) - \text{prob}(S_2,B|M_k)$. Curves start from the prior assignments and converge to the condition simulated. At time $t = 18$ days the settlement scenario is still unlikely, however the system already recognizes that, if any settlement is under way, the correct

![Figure 12a](image1.png)

![Figure 12b](image2.png)

**Figure 12.** a) Scenario probabilities and b) time risk for a simulated settlement.
response model is B. At \( t = 22 \) days the probability of a settlement starts to increase up to the point that at \( t = 27 \) days there is confident identification of a settlement.

Using recursively Equation (11) we can update the estimate of the future risk of cracking \( \text{prob}(X) \) at the frescos. Figure 12b shows how \( \text{prob}(X) \) changes with time. Despite the prior probability of failure being almost negligible, the estimated risk grows rapidly after 3 weeks from the start of work: namely, \( \text{prob}(X) \) is higher the 1/100 at day 24, higher than 1/10 at day 26 and higher than 50% at day 27. Evidently, after just 24 days the level of risk is intolerable, suggesting the system manager must take immediate action, for example suspending the work. This shows that, at least in this case, the identification algorithm can highlight the risk well in advance respect to the actual occurrence of damage.

It is interesting to analyze how the distributions of the scenario parameters change with time. Figure 13 reports contour plots of the joint distribution for parameters \( \delta_\infty \) and \( \lambda \) at different identification times, calculated according to Equation (10). More specifically, the first column reports \( \text{PDF}(\delta_\infty, \lambda | M_k, S_2, A) \), the distribution given Model A, the second column reports \( \text{PDF}(\delta_\infty, \lambda | M_k, S_2, B) \), the distribution given Model B, and the last column shows \( \text{PDF}(\delta_\infty, \lambda | M_k, S_2) \), obtained by marginalization on model parameter \( b \).

As expected, uncertainty on the parameter decreases as more measurements are available, although we observe that the level of uncertainness remain very high. For example, after 20 days, the estimate of the parameters is still very inaccurate. At 50 days, if no action has been taken, the building is near failure and the mean values of the parameters are actually very close to the real ones; however, their joint distribution reveals that the system is not fully convinced about the final value \( \delta_\infty \) of the settlement. Observe also that after 100 days, when in essence the settlement has fully developed, the algorithm correctly identifies parameter \( \delta_\infty \) (\( \delta_\infty = 7.0 \pm 0.9 \text{ mm} \)) yet it is unable to tell with the same degree of accuracy the velocity at which the phenomenon has occurred (\( \lambda = 0.035 \pm 0.01 \text{ day}^{-1} \)). This uncertainty in early prediction of the parameters of the scenario is perfectly consistent with the high level of noise involved in the measurement. In simple terms, this is not a matter of algorithm but of information: we can qualitatively appreciate this fact comparing ideal and measured response in Figure 11. Nonetheless, observe that the effectiveness of the system is not critically dependent on its ability to identify the model parameters but rather hinges on its capacity to account for all uncertainties and to provide a consistent estimate of the risk: for example after 27 days, the system still cannot provide detail on the ongoing phenomenon, yet it is perfectly aware that a settlement is occurring (Figure 12a) and can warn the manager of the high level of hazard involved (Figure 12b).

5. CONCLUSIONS

In this article, we have presented the outline of a framework for 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 visual inspection and online monitoring systems. The system exploits low-cost distributed sensing technology and Bayesian 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
Figure 13. Joint distribution of parameters $\delta_\infty$ and $\lambda$ for scenario $S_2$. 

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and on the risk associated. 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 operation of HHMS has been illustrated by the specific case of the Aquila Gate in Trento. The risk-updating algorithm is applied with a real-life issue in mind, which is the preservation of the integrity of the frescos during future tunneling work. The general methodology adopted in HHMS allows us to deal flexibly with all the uncertainties involved in the problem: measurement noise, uncertainty on the model and inaccurate prior information. In the specific case, the result of the simulated day-by-day risk analysis shows that the identification algorithm can highlight a hazardous condition many days in advance respect to the actual occurrence of damage. Although the overall procedure has been illustrated having in mind a specific case, the general approach is not problem dependent and can be extended to a broader class of problems, including manifold scenarios, material uncertainties, as well as prior knowledge of parameter distribution.

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REFERENCES


Istituto Centrale per il Restauro (ICR). Available at: http://www.icr.beniculturali.it/ (accessed January 27, 2008).


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