Cover sheet

Title:
Real-time health monitoring of historic buildings with wireless sensor networks

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ABSTRACT

This paper describes the application of a wireless sensor network (WSN) in Torre Aquila, a 31 meter-tall medieval tower located in the city of Trento (Italy). Special attention was paid to monitoring and preservation of an artistic treasure: the fresco of the "Cycle of the Months" on the second floor. The various 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 structural model parameters and to identify any possible occurrence of abnormal situations. Strain sensors include prototypes of new Fiber Optic Sensors (FOS) in view of their long-term stability and durability. Based on the first 8 months of operation in assessing the stability of the tower, the wireless system is seen to be an effective tool thanks to its customized hardware and dedicated software. The whole system is reliable and energy efficient. The comparison between the acquired measurements and simulated numerical results shows good agreement.

INTRODUCTION

Wireless sensors and wireless sensing networks, due to their low installation cost, highly scalable features and low-level invasion of host structures, have been applied to structural health monitoring to replace conventional cabled monitoring systems. A wireless sensor (usually called sensor node in a wireless sensing network) can be viewed as an updated version of the traditional sensor, which works as an autonomous data acquisition node with wireless communication [1]. Moreover, wireless sensors can play a greater role in processing monitored data by moving the intelligence closer to the measurement point [2].

Many products are now commercially available to be integrated into a wireless sensor network for structural monitoring applications. Straser and Kiremidjian [1] proposed a low cost wireless sensor for structural monitoring, choosing a Motorola 68HC11 microprocessor as the computational core for its many on-chip hardware

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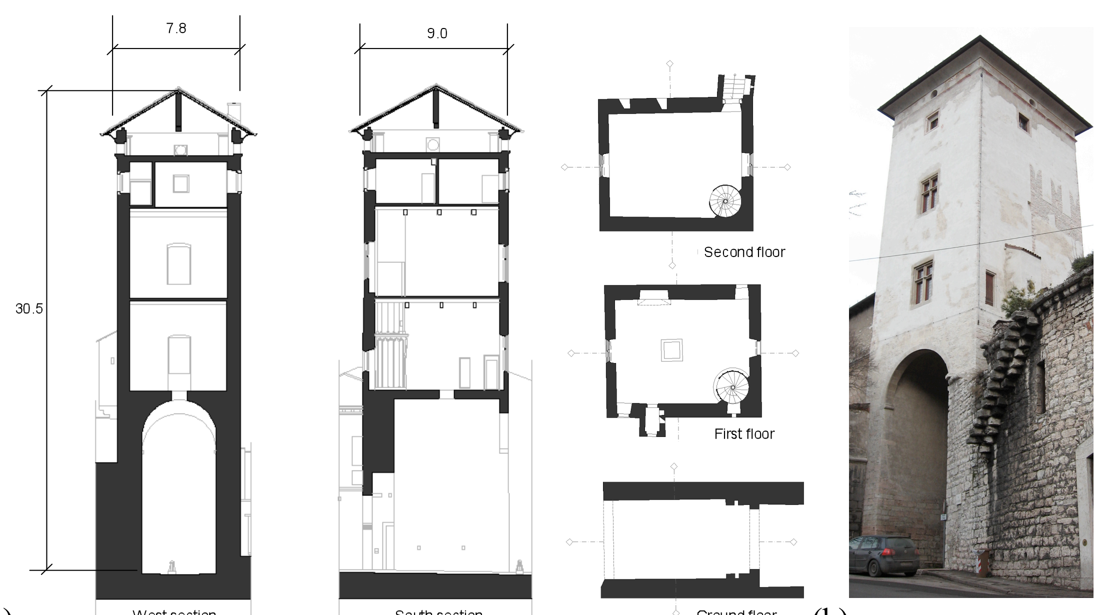
peripherals, and a Proxim Proxlink radio as transceiver for reliable wireless communication. Lynch et al. [3] proposed a wireless sensor prototype using the 8-bit Atmel AVR AT90S8515 enhanced RISC (Reduced Instruction Set Computer) microcontroller, a Texas Instrument 16-bit ADC and the Proxim ProxLink MSU2 wireless modem operating on the 902–928 MHz ISM radio band for low power consumption. To integrate the computational capacity into the sensor node, a number of engineering analyses, such as damage detection and system identification, have been embedded in the wireless sensor unit to allow decentralized architecture in structural health monitoring. For more information, see the summary review by Lynch [1].

However, most off-the-shelf wireless sensor nodes are not produced specifically for civil engineering. Unnecessary integration of components in a wireless node increases the cost and power consumption, hardly satisfying the requirements of structural health monitoring. In our paper, a customized wireless node integrated with highly reusable and easily extensible software services is proposed especially for application in a historic tower. First the tower is described to clarify the monitoring objective, then the installation of the whole system is presented. In the final section, system performance and monitoring results are discussed.

HISTORIC TOWER DESCRIPTION

The Aquila tower, a part of Buonconsiglio Castle, is a 31 m tall medieval tower built in the 13th century, located in the city of Trento in Italy. As described in the paper [4], the tower was once a part of the wall and was intended to guard the city gate. It was later further elevated, extended and joined to the castle in the 14th century. The tower has five floors including the ground level entrance (Figure 1). Except at ground level, the floors have a rectangular plan size 7.8 m×9.0 m. Although the tower appears symmetrical, mechanical responses are asymmetrical,



(a) (b)

Figure 1. Plan view and cross sections of the tower of Aquila (a); Overview of the tower (b).

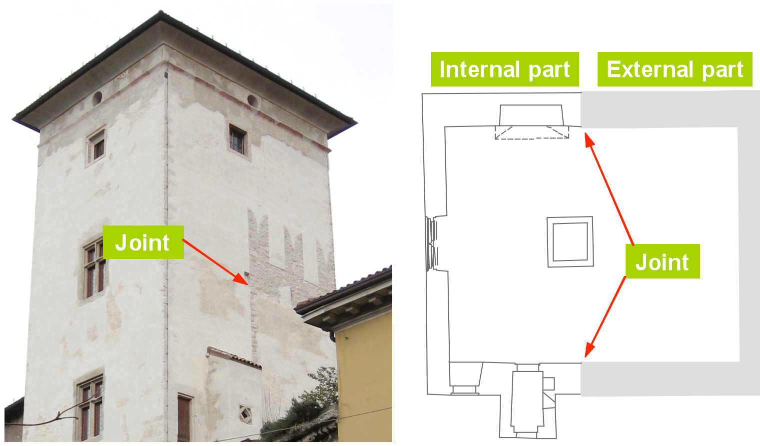


Figure 2. Structural joint in the wall of tower.

due to a number of structural factors. First, the connections to the city wall and to the adjacent buildings are asymmetrical and have significant effects on the tower's structural response. Second, the two independent construction phases produced a clear structural joint in the tower (Figure 2). An endoscopic test showed that the two parts of the masonry body exhibit completely different stratigraphic and mechanical properties.

Today the castle is open as a historical museum, and the Aquila tower attracts exceptional attention to the artistic treasures on the second floor: the cycle of frescoes called "the Cycle of the Months" is a unique example of non-religious medieval painting in Europe. The preservation of these frescoes is the main source of concern for the local conservation board.

DESIGN AND INSTALLATION OF THE MONITORING SYSTEM

In order to obtain enough relevant information to analyse the current condition of the tower, 16 sensor nodes plus one base station were deployed on the first four floors (Figure 3(a)). To identify the dynamic properties of the tower, three acceleration nodes #144, #145 and #146 were installed to record vibration information. The first was located on the ground floor to record the external excitation to the tower, and the other two were installed on the third floor to record the vibration of the tower. Due to the asymmetric structural response of the tower and the existence of the joint, a coil FOS (#154) node was deployed along the wall to monitor the crack condition on the 1st floor (Figure 3(d)). In order to detect the inclination of the tower resulting from vibration or non-uniform settlement, another very long FOS (#153) was installed along the wall corner with one end entering the tower through the roof (Figure 3(e, f)). Both FOS were calibrated in the laboratory before installation [5]. As well as the above, 11 environmental nodes (Figure 3(b)) were distributed on the floors to monitor the temperature and humidity conditions. In the WSN, the sampling frequency of vibration nodes were characterized as 200 Hz to capture the dynamic properties, while the FOS and environmental nodes are set to gather 1 sample per minute.

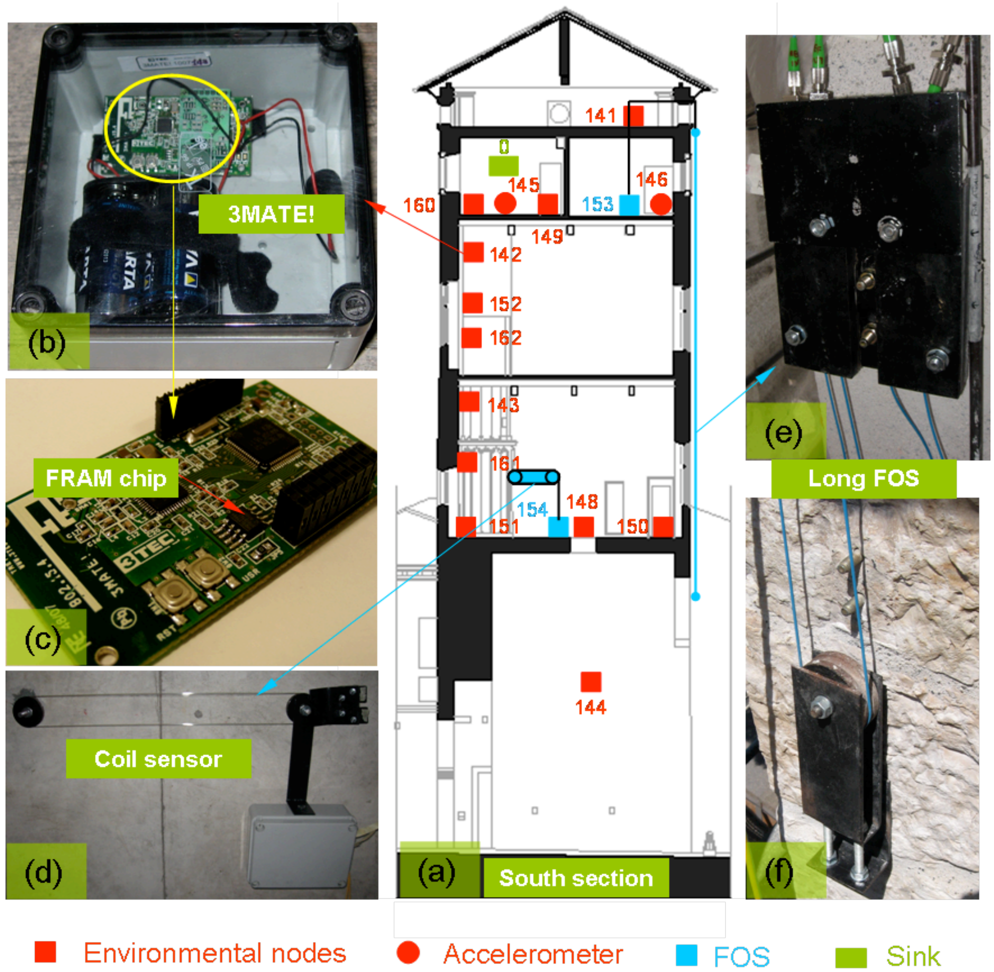


Figure 3. Deployment of WSN in south cross section (a); a wireless node (b); 3MATE! module (c); coil FOS (d); upper anchorage of long FOS (e); lower anchorage of long FOS (f).

To provide the computational core and communication functions, we integrated each of the sensors described above with a corresponding 3MATE! WSN module (Figure 3), developed by TRETEC (www.3tec.it). The 3MATE! is a TMote-like [5]-device equipped with an 802.15.4-compliant radio chip and an internal microstrip antenna. Specifically, the nodes attached to the vibration sensors were also equipped with an additional FRAM chip to allow for energy-efficient temporary storage of vibration readings (Figure 3(c)). Unlike traditional flash technology, FRAM provides faster read/write operations and a higher number of read/write cycles before the data stored may be corrupted.

At software level, we implemented a custom multi-hop data collection protocol to report sensed data to the user. This operates at very low power to provide extended system lifetime, and guarantees very high reliability for both low-rate data such as temperature and for high-rate data such as vibration. This is achieved using different techniques depending on the nature of data being communicated [6]. We also implemented a lightweight time synchronization protocol to correlate readings at different sensors, and a tasking functionality that allows the user to change the operation parameters (e.g. sensing period) remotely. Unlike most WSN deployments reported in the literature, the aforementioned functionality sits atop a middleware layer called TeenyLIME [7]. This makes it simpler to implement the processing required, ultimately yielding more reliable and re-usable implementations. This approach sharply differs from traditional solutions where the application mechanisms are implemented directly using the operating system or with no operating system support [1].

DATA COLLECTION AND ANALYSIS

The whole wireless sensing system started to work in September 2008. In the past eight months, the whole system is under examination and debugging. For most of the time, the data corresponding to environmental phenomena, tower deformation and dynamic vibration behaviour were monitored and acquired continuously save during the periods of adjusting and updating the monitoring system, such as in March 2009, when the system stopped working. In order to check transmission reliability, the data loss is under inspection. In recent months, the overall loss rate is assessed at less than 0.01%. This is good performance if compared with other long-term wireless sensor network deployments reported in current literature [6].

In the paper [4], a three-dimensional Finite Element Model (FEM) of this tower

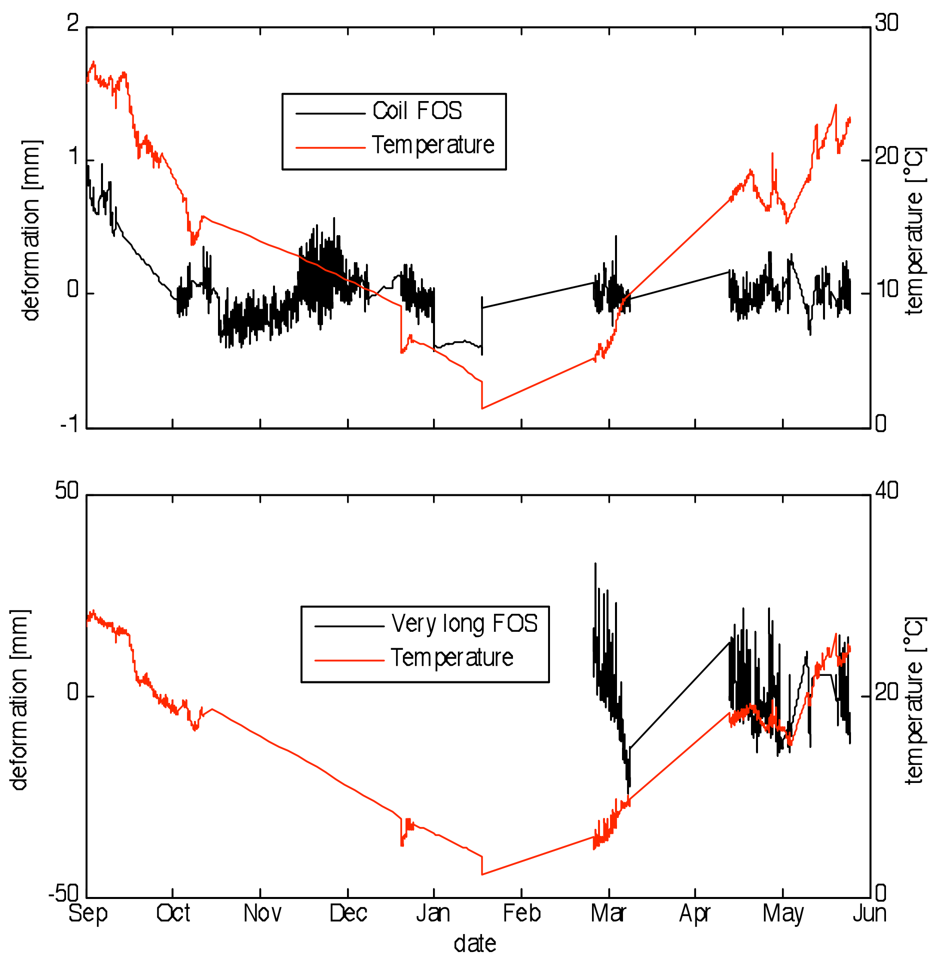


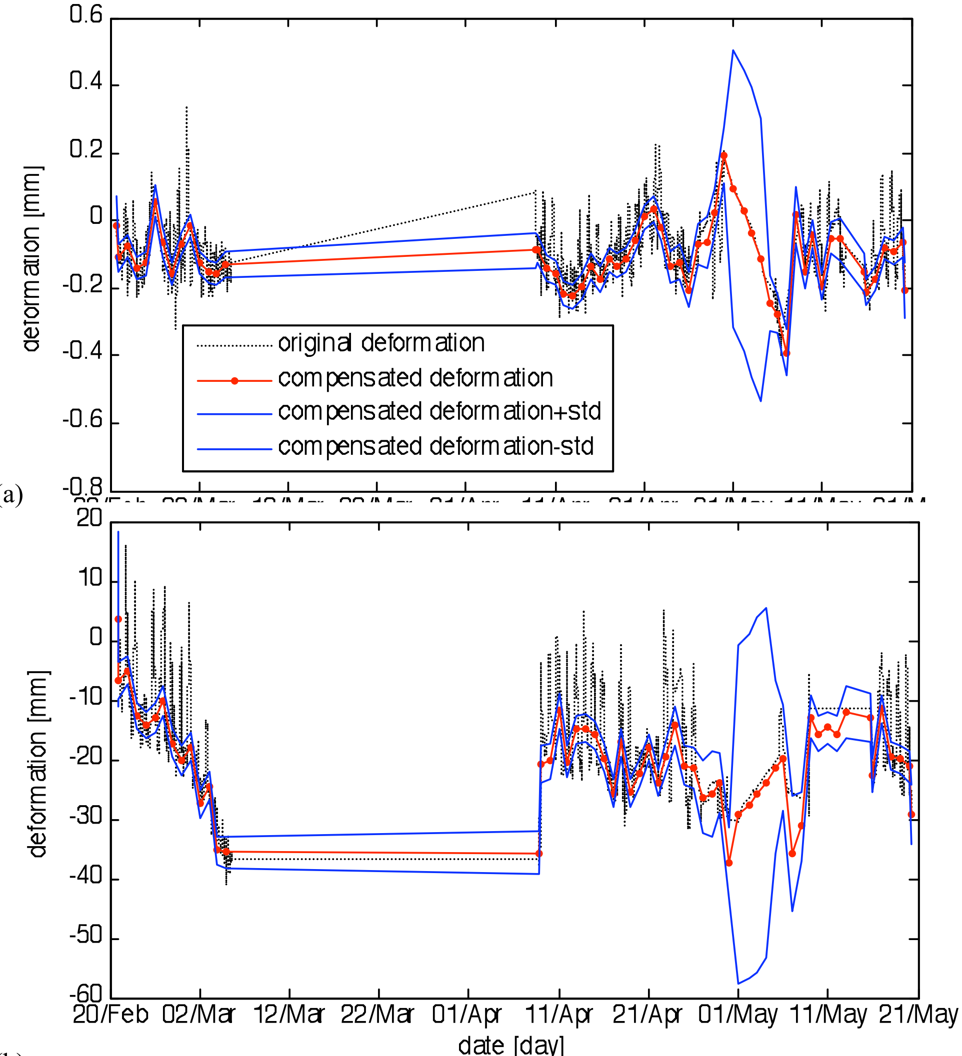
Figure 4. Deformation time history recorded by coil FOS (top) and long FOS

was established and discussed under different load and environmental conditions. The simulation results show that: compared with other factors (such as wind and snow), thermal gradients produce the largest absolute strains in the tower; only a minor part of these is stress-induced. For example, the thermal distortion of the crack is estimated as 0.157mm on a summer day, and 0.069mm in winter; however, the response of the coil sensor from the 10mm settlement at the southwest foundation is estimated to be 0.0023mm. Figure 4 shows the deformation records from two FOS with their corresponding temperatures. Figure 4 (top) presents the deformation measured by the coil sensor from September 2008 to May 2009. The amplitude in a daily variation cycle is between 0.05mm and 0.30mm, which is in good agreement with the numerical results of the FEM model. Figure 4 (bottom) shows the temperature records from node #153 since last September and its deformation measurements from February to May. This large loss in the deformation records was caused by problems in the interrogation unit of the long FOS before February. If compared with the predicted value (with a thermal distortion of 3.87 mm on a summer day) presented in the paper [4], the acquired measurements obviously give a greater amplitude. This difference may result from the changed setup of the interrogation unit caused during the installation and system updating. However, the real reason needs to be reconfirmed with more available data in future.

In our project, special attention was paid to measurements relating to the fresco. Evidently the two FOS are the main relevant sensors responding to the structural condition of the frescoes. Since damage to the frescoes is caused essentially by stress-induced strain, we must investigate the compensated strain to remove the temperature dependent effect. In this paper we try to apply a Bayesian algorithm [4, 8] to process the large amount of data. In this case, the two FOS are regarded as *response sensors*, to record the structural response of the tower, and thermometers in the relating nodes are viewed as *environmental sensors*, to record the environmental effects. We assume $m_{i,j}$ to indicate the measurement sensed by *response sensor j* at time *i*, and $h_{i.k}$ to denote the measurement recorded by *environmental sensor k* at time *i*. In order to remove temperature dependent effects, we organize the time history into a series of small time intervals (say each day), with the assumption that the intervals are small enough to ensure the change of compensated response within an interval be negligible. The temperature dependent deformation was assumed to have a linear relationship with temperature, but suffers a time shift between:

$$m_{T,j} = m_{0.j} + \alpha_j \cdot h_{T+\Delta T.j} + m_{n.j} \tag{1}$$

where $m_{T,j}$ is the deformation sensed by sensor *j* in time interval *T*, $m_{0.j}$ is the compensated response, α_j is a linear coefficient, ΔT is the time shift between deformation and temperature, and $m_{n,j}$ is the noise component resulting from instrumental and environmental noise. ΔT could be obtained by analyzing the deformation from the FOS compared with the corresponding temperature. Then based on the measured temperature and deformation records, we can formalize a rigorous Bayesian procedure to identify the compensated deformation [4] to remove the temperature dependent deformation. Figure 5 shows the estimated compensated deformation from both FOS.



(a)

(b)

Figure 5. Estimated compensated deformation from Coil sensor (a); Compensated deformation from very long FOS (b).

The linear expressions fitted between compensated deformation and time are indicated as follows, respectively corresponding to coil sensor and very long FOS:

$$\begin{aligned} \Delta d(mm) &= -0.092(\pm 0.058)\cdot \Delta t(year) \\ \Delta d(mm) &= -25.95(\pm 4.66)\cdot \Delta t(year) \end{aligned} \tag{2}$$

where Δd is the change of compensated deformation, and Δt is the time variation. The number inside the parenthesis is the standard deviation.

From the above estimate, the coil sensor shows a small change trend (0.034~0.15 mm/year). However it is hard to say now, based on available data, whether this change trend is caused by permanent damage to the tower, such as non-uniform subsidence, or is just a seasonal trend. Certainly, as more and more data become available, we can identify the real influences causing this phenomenon. While the wall deformation recorded by very long FOS exhibits a greater change rate which is not reasonable. The possible reason may result from its changed calibration factor. A special newly designed calibration test will be necessary since the FOS has been deployed in the tower.

CONCLUSION

A structural health monitoring technology based on WSN technology has been applied in the Aquila tower to monitor its structural integrity. To allow reliable wireless communication at low cost and with a long service life, the 3MATE! module was selected as the core platform, and a TeenyLIME based multi-hop data collection protocol was applied to improve the system's flexibility and scalability. In recent months, the data loss ratio was estimated as less than 0.01%.

Analysis of the acquired data gives good agreement with the predicted results estimated from the 3-dimensional FEM. For example, the data acquired from the node interfaced with the custom-built coil sensor for crack monitoring clearly show the usual daily variation cycle with an amplitude of between 0.05mm and 0.30mm, which is in good agreement with the FEM results. The estimated compensated responses indicate that there is a small change trend in the wall, however, more monitoring data are needed to see whether this change is caused by seasonal trends or some kind of structural damage, such as non-uniform subsidence.

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