AUTO-REGRESSIVE COMPENSATION TECHNIQUE FOR A RELIABLE NON INVASIVE STRUCTURAL HEALTH MONITORING SYSTEM

Berardo Naticchia, Massimo Vaccarini, Alessandro Carbonari*, and Pierpaolo Scorrano

Department of Architecture Construction and Structures – Division of Building Construction
(Engineering Faculty), Università Politecnica delle Marche, Ancona, Italy
** Corresponding author (alessandro.carbonari@univpm.it)*

ABSTRACT: Detecting the health status of buildings is critical to produce correct diagnoses that could prevent many pathologies, as well as driving maintenance interventions through timely and well targeted operations. The constant innovation in the development of low power wireless sensing devices provides an unparalleled chance to develop efficient monitoring system prototypes, conceived to be very low intrusive and operating in real-time, that can be applied also on existing buildings, without any need to predispose chases for power conveyance or communication cables. Its adoption is expected to be useful not only for standard health status monitoring of buildings during their lifecycle, but also for automated monitoring of old buildings during the execution of renovation works. The latter being referred to the possibility that unexpected collapses may endanger the conditions of workers engaged on the construction-site, where alerting in advance would prevent many deaths on the job. In this paper a low-power, wireless, easily installable structural monitoring system based on tilt sensors is developed, on which several integrated logics for automated control of building's health conditions are implemented. As its preliminary evaluation on a real building demonstrated that external temperature variations cause inaccurate measurements, an experimental setup capable of reproducing dynamic conditions due to environmental actions on the system has been developed. It was used both for developing an autoregressive model to be implemented for temperature compensation, and to perform its validation. The technologies and logics for remote automated monitoring are presented.

Keywords: *Structural health monitoring, real-time control, dynamic temperature compensation, autoregressive models.*

1. INTRODUCTION

This paper investigates about the feasibility of a reliable tilt sensor node, as the main component of a more complex real-time structural health monitoring system. One of the biggest benefits it can provide is given by its untethered and wireless features and, consequently, easy on-site deployment. It is made up of a wireless and self-powered communication system, which supports data transfer from sensors and probes installed on buildings to any local or remote server. Several other commercially available communication networks may be adopted for communication to remote server [1]. Remote monitoring from anywhere in the world will be possible by a common internet browser. In line with the general approach characterizing this system, even the structural monitoring sensors are expected to be self-powered, regardless their specific typology.

Effective and comprehensive health monitoring practice in construction has always asked for the adoption of plenty of sensors due to the complexity of targeted structures: in order to perform a thorough dynamic structural health evaluation of a 610m tall tower, accelerometers, gages, fibre-optic strain sensors, laser based displacement sensors, and so on, have been installed and wired connected to a central acquisition system located in the building itself [2]. Similar challenging works have been accomplished for monitoring a building under retrofitting [3] and progressively predicting life time expectancy of bridge structures, through continuous refinement based on the data collected by a monitoring system [4].

Several authors have stressed the necessity of remote access to monitoring systems' data of critical infrastructures, in order to evaluate in real-time their health status and prevent them from endangering users [4, 5]. While agreeing with the necessity for real time control, the authors also highlight that those systems should become easily deployable on site, possibly without cabling, in order to result as cheap as possible, even in case of installation on the existing building stock. In addition, in case untethered and full wireless capabilities are successfully coupled with automated and real-time control of data, then the control system can be used even in construction site's safety management. In fact, when construction firms send their employees to retrofit old buildings, they risk sudden collapses due to actions generated by the interventions themselves (e.g. induced vibrations by drilling machines). As a real-time monitoring system would be capable of predicting those events and warning for fast evacuations, risk figures would dramatically fall. Hence the system described in this paper, once properly developed, would conform to multiple purpose applications.

The work presented in this paper considers the development of tilt sensors as main components of a more complex monitoring system. All the developed sensors are self-powered (thanks to their low consumption features), in order to keep the wireless nature of the whole framework. The tilt node has been characterized and its behaviour analyzed in a real environment, which has unveiled the temperature drift risk. Due to that, an autoregressive model for temperature compensation has been developed. The final validation shows its feasibility and paves the way to further technology integration in the general system framework presented afterword in this paper.

2. REQUIREMENTS ANALYSIS AND DOMAIN

The multiple purpose applications of the system include renovation construction sites and health and safety monitoring of the existing building stock, where historical town centers represent a relevant target. This is one of the main reasons why the system must be low invasive: in order to not interfere with the tasks in progress on site and in order to be easily deployable even on existing buildings, where invasive interventions, such as chases, may be too expensive or not allowed (e.g. in historical buildings). Fig. 1 depicts how the whole system could be set on a bell tower. It is conceived as a set of small, light and easily deployable devices, which wirelessly communicate one another and to a central server responsible for data acquisition. Two kind of deployable devices are foreseen: the first one having the main task of monitoring any structural parameters and broadcast these data (e.g. strain, stress, displacement etc..); the second ones (called routers) as a part of a communication backbone, which forwards those data towards the Central Application. All those devices are expected to work outdoor, hence they must be resistant to harsh environmental conditions. In this study the sensors were developed to be able to monitor rotations on historical structures.

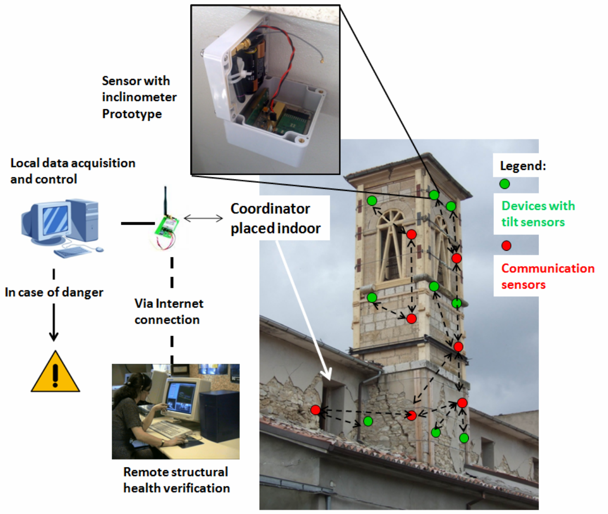

Fig. 1 The whole system under development.

The order of magnitude of the parameters to be measured were inferred by analyzing the structural behaviour of the bell tower depicted in Fig. 2-a, as extensively explained in [1]. The analysis is compliant with the current legislation regarding structural response under seismic actions [6]. As the monitoring system is expected to alert before the structure reaches collapse, then deformations corresponding to damage limitation states have been estimated. A finite element linear elastic model of the structure has been built and simulated through SAP 2000^{TM} software program. The point where the maximum rotation has been recorded, marked by a red circle in Figure 2-b, a tilt value of 0.15 deg has been detected. Hence the system is expected to have a repeatability of at least 0.05 deg or better, so that it alerts before collapse takes place.

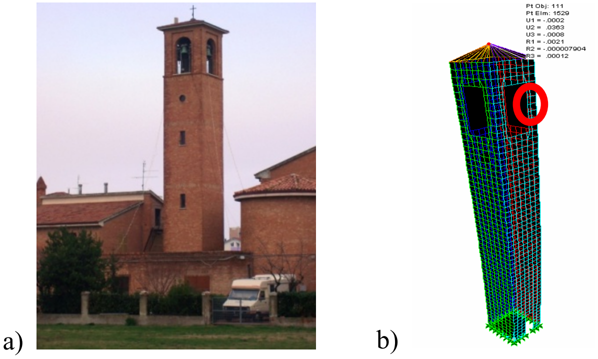

Fig. 2 Masonry bell tower chosen as a test case for the structural analysis (a) and FEM model (b).

3. MONITORING SYSTEM

The inclinometer sensor node developed in the research step described in this paper is the one to be installed on buildings for their monitoring. The data acquired are then transferred to a local coordinator over a communication network built on the topology shown in Fig. 3.

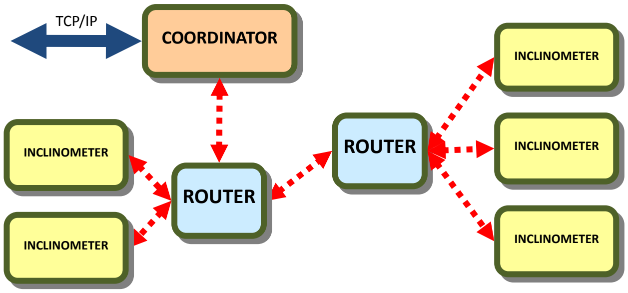

Fig. 3 Typical network topology.

A True Tilt^{TM} sensor, patented by the Fredericks Company^{TM}, has been embedded in the node. It is an electrolytic inclination sensor with a maximum operating range of ±2° and, thanks to its high resistive behaviour, it does not sensibly affect power consumption of the whole device. Its resolution is better than 1 arc second (about 0.0003°) and the null repeatability better than 5 arc seconds (i.e. 0.0014°). Since the tilt sensor must be driven with a zero mean value supply signal applied between the two ends (pin 1 and 3), a decoupling capacitor has been introduced between the digital buffer and the tilt sensor. It was calibrated to limit the voltage decay in the analog to digital (AD) conversion and to allow complete discharge of the capacitor during turn-off period, at advantage of its stability. A power-saving microcontroller (μC) wakes-up every second, acquires data and transmits it, provided that a significant variation has been detected or according to a defined timeout set at 20 s. It is equipped with a temperature sensor, too.

Thanks to an experimental installation of the system on an old country house over three months in the spring 2010, it was possible to infer that temperature shifts cause reading instability. In particular, even though the two inclinometers were installed side by side, they measured different tilt variations (never higher than 0.03°), which might be explained as a result of the different temperature influence on their behaviour. For that reason, it was decided to develop a temperature compensation model, to make it more reliable and accurate.

3.1 Calibration

In order to characterize the static behaviour of the device, four inclinometers have been calibrated by applying a number of known inclinations and recording the response. Four calibration curves, in the form of 6th order polynomial curves fitted in the ±1° domain through the Least Squares regression method, have been obtained. Their reciprocal comparison showed that calibration curves are significantly different, being the smallest difference among them equal to 0.014°, which is too close to rotations to be measured. This imply the necessity of calibration for each transducer.

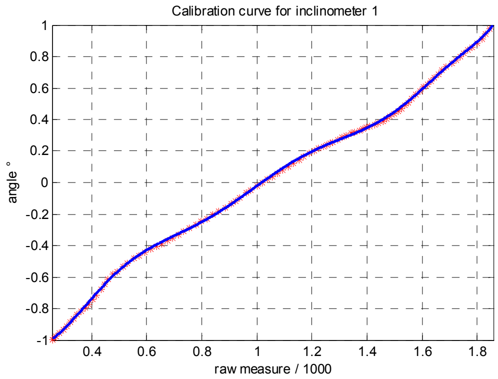

Fig. 4 Calibration curve for sensor 1.

3.2 Sampling interval and delays

The sampling time was determined according to the Shannon theorem [7]. Starting from the analysis of the impulse response, the frequency spectrum was computed. Then the frequency value corresponding to an amplitude reduction of 3dB was estimated as B_3=0.0115Hz. Applying the empirical relation $T_s=3/B_3$, the settling time came out to be equal to 260s, hence the sampling time must be included between Ts/15 and Ts/8 (between 17 and 32s). Combining this outcome with Shannon Theorem, requesting a sampling frequency higher than $2 \cdot B_3$, the value 30s (0.033Hz) was adopted.

Temperature measurement was performed through a transducer embedded in the microcontroller that manages the inclinometer. In order to estimate whether a delay in the temperature sensor's reactivity must be taken into account, a step response was analyzed. By comparing the rise-time of the temperature step and the one of the inclinometer, it was estimated that temperature measures are 2 min late with respect to angle variations. Hence, for making the system causal, every temperature acquisition series were shifted by 2 min ever after. No significant delay was checked regarding the inclinometer's reactivity to angular variations.

3.3 Data gathering on temperature drift

As a first step, a proper input sequence for system identification were generated being persistently exciting of sufficient order. For this purpose input temperature courses were driven by means of four types of stimulating inputs, each labelled by a number increasing with the level of supplied heat: cool external wind and fan on (labelled with 0); cool external air (1); electric heater set at 800W (2); electric heater set at 1200W (3); electric heater set at 1200W and next to the inclinometer (4). Matlab^{TM} software was used to generate a random sequence made up of 100 stimulating inputs numbered from 0 to 4, associated to two random series of time durations for each stimulation entry; the total duration of each stimulating series was set to 9 hours. The resulting sequence was tested to have sufficiently small autocorrelation in order to be sequentially uncorrelated. Inclinometer no. 1 was placed on the window sill of a bulky wall, which guaranteed stability in the short run. The system has been inputted with the previously generated sequence and the resulting rotations have been recorded as outputs.

The graph in Fig. 5 shows the temperature and rotation courses measured by the node when subject to the first series of stimulating inputs. The temperature swings were considered high enough (up to 55°C) to be representative of the worst environmental conditions the inclinometer may be realistically exposed to. As a consequence, the inclinometer measured apparent tilt variations are included within about 0.04°.

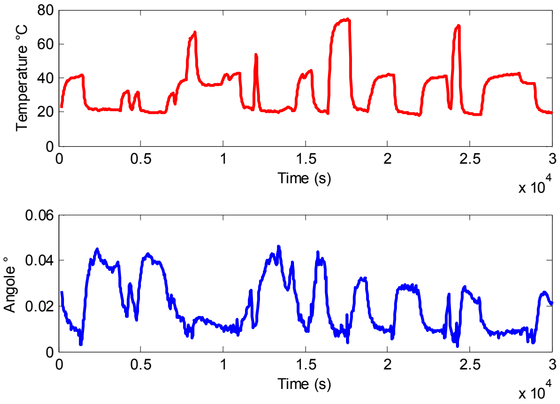

Fig. 5 Stimulating input and measured output.

3.4 Estimation of the temperature compensation model

Temperature compensation was performed by identifying a temperature response model according to the following procedure: data collection as in paragraph 3.1; choice of the best model and corresponding parameters estimation; model validation, which is the object of the paragraph 3.3.

ARX (AutoRegresive with eXternal input) models were used to infer the angle drift caused by temperature variations [8]. The general ARX model equation is:

$$A(z)y(t) = B(z)u(t-1) + \epsilon(t) \qquad (1)$$

where $A(z)$ and $B(z)$ are polynomial in unit delay operator z^{-1}, $y(t)$ is the system output at time t, $u(t)$ is the system input and $\epsilon(t)$ a white noise with zero mean value.

Two models have been estimated: the first one to be chosen as the best one step ahead predictor and the second one as the best simulator. At each step, the predictor uses all the available measures for predicting the next output, while the simulator uses previous predictions instead of measures for making its forecasts.

The MatLab^{TM} Identification Toolbox was used first to merge the two time series collected as reported above in paragraph 3.1 at two different angles, and then to estimate the best one step ahead predictive ARX model including one exogenous input variable (i.e. temperature) and one endogenous variable (i.e. inclination angle). It was found that 3rd order models gave back acceptable reliability and, among the tested ones, the ARX$_{311}$ was selected because of its excellent fit (93.6% at one step ahead and 57.99% at five step ahead), its rather low complexity and low degree, its high stability (i.e. poles and zeros within the unitary radius circle). Eq. (1) in this case is fitted by the following coefficients:

$$A(z) = 1 - 2.138(\pm 0.030)z^{-1} + 1.495(\pm 0.057)z^{-2} - 0.358(+0.030)z^{-3}$$

$$B(z) = 0.283 \cdot 10^{-3}(+0.070 \cdot 10^{-3})z^{-1}.$$

The best simulator model, still based on eq. (1), resulted to be an ARX$_{111}$ type, with the following coefficients:

$$A(z) = 1 + 0.862(\pm 0.075)z^{-1}$$

$$B(z) = -0.873(+0.124)z^{-1}.$$

It reaches good stability and a fit accuracy as good as 31.32%, much lower than the previous case but acceptable for long term simulation estimation (Fig. 6).

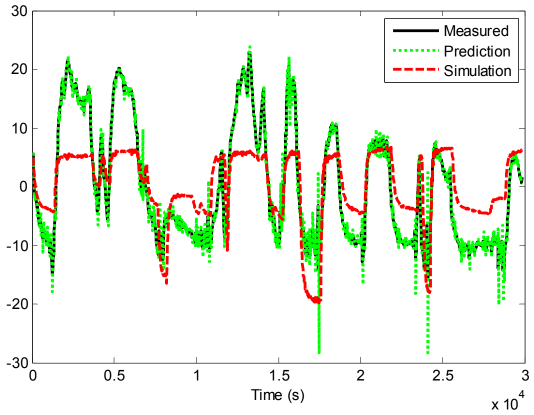

Fig. 6 Fitting accuracies.

3.5 Control logics for real-time alerting

As mentioned above, the monitoring system to be installed on buildings must alert well before rotations (e.g. of the bell tower in paragraph 2, chosen as test case) reach its damage limitation state. However the rate at which such a deformation threshold is approached may vary and be either gradual or quick . So the final control logics should rely on several logics, each targeted to a different time horizon and based on pre-defined alert thresholds (over the threshold an alarm will be triggered):

1. sudden movements (e.g. caused by earthquakes or induced by accidental actions) take place within few seconds or less and are not affected by temperature, hence the raw measures outputted by the inclinometer are directly used;
2. for detecting tilt variations in the short run (i.e. few minutes) the system will use the predictor model described in paragraph 3.4 to compensate the temperature variations' effect and work out the real building estimated rotation;
3. for time windows of several hours, temperature compensation will be performed through the simulator model in paragraph 3.4;
4. in case tilt variations are had over one or more days, compensation is not needed, because temperature courses are cyclical and it is enough to compare average rotation values from day to day (or multiples).

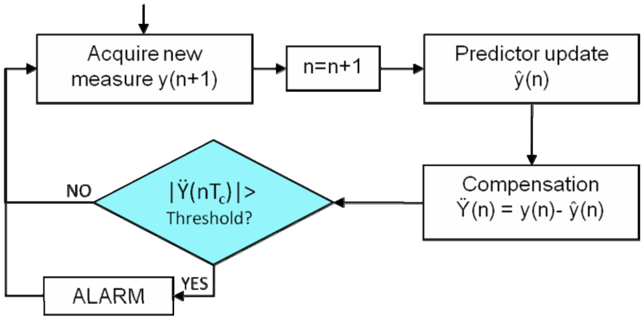

Fig. 7 Automated control logic no.2 used in the short run.

The integration of the four control logics is critical to assure a timely alarming system. In this way, it will never happen that rotations are so slow that the system cannot predict a critical situation.

3.5 Validation tests

Many validation tests have been performed by comparing the outputs of the control logics with respect to the inclinometer's tilt variation, which was detected by means of a parallel mechanical inclinometer manufactured by Officine Galileo^{TM}, sufficiently insensitive to temperature variations.

Fig. 8 shows a controlled experiment, where the inclinometer was made slowly get tilted through seven induced rotation steps (marked by the upwards red arrows at the bottom) whose amplitude was included between 0.007° and 0.0498°. In the meantime the temperature was left to vary. The red line in the diagram shows the raw data acquired by the inclinometer, while the green line represents the compensated course. It can be noticed that at any angle variation the green line undergoes a sudden step, which is easily detected. Three other trials gave back the maximum step caused by high temperature steps (till 50°C) was never higher than 0.05°. Hence this was set as the threshold, which brought the peaks marked with the red crosses in figure, triggering as many alarms.

Similar validation tests were performed in the case of a sudden rotation, no rotation but high temperature variations, slow deformation, always obtaining a very good performance from the inclinometer.

Finally, a first polycarbonate made and parallelepiped shaped casing resulted to affect only partially the compensation quality.

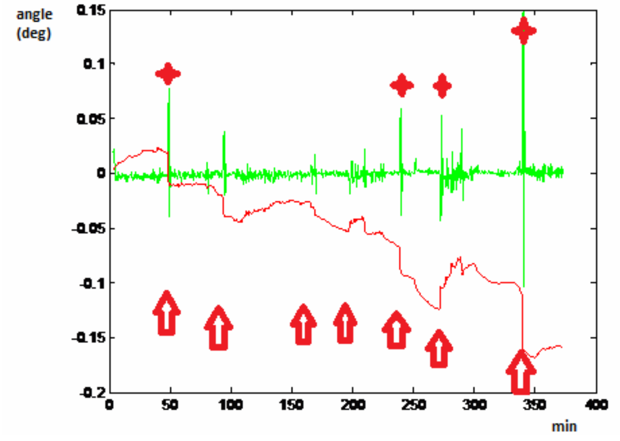

Fig. 8 Validation of control logic no. 2.

4. CONCLUSIONS

A wireless, low power and non invasive structural monitoring system has been developed, capable of monitoring tilt variations in real-time. Two auto-regressive models were estimated and implemented to compensate temperature drifts, showing their reliability in simulated contexts and making the inclinometer capable of detecting even very small tilt variations, typical of the old building stock. Presently some research is ongoing about the best casing to be chosen, in order to not degrade the overall sensor accuracy.

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