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Large Scale Monitoring System for Existing Structures and Infrastructures

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Abstract. Most of the key structures of highways and railways systems in Europe and North America has been built after Second World War during the economic boom that took place between the 50s and the 70s of the last century. This heritage of existing infrastructures and building of the "Western World" is nowadays subject to a natural and gradual aging process, induced by the progressive deterioration and the age of the structures, which causes a consequent functional obsolescence. This process develops with continuity and therefore can be controlled over time and can become foreseeable in most cases. Adequate scheduled maintenance can then be applied to keep the safety levels and the performance of the structures aligned with standards requirements. The best way to control ageing and deterioration is the implementation and installation of diagnostic systems for the estimation of constructions safety levels and operating conditions. This monitoring systems are known and used since many decades, but have never been toughly applied as a standard in civil engineering works as it has happened for instance to the automotive field. Traditional monitoring systems of infrastructures require careful assessment of the current state of the artefacts, through detailed and targeted surveys, expensive laboratory instruments and highly skilled labour. This article presents two diagnostic systems based on an innovative, affordable and minimally invasive monitoring, able to provide the user with real-time information on the state of health of the structure. The system is composed of low-cost sensors, capable of monitoring various physical quantities, and connected to each other with different technologies for data transfer and sensor power supply. The recorded data are initially processed directly on board, then sent to the cloud, where they can be further processed or made available for subsequent processing or for a comparison with the expected response calculated using mathematical models of the structure.

1. Introduction

Structures aging and conservation are matters of concern for safety of all the users. The panorama of buildings, real estate and infrastructure heritage is subject to a natural and gradual aging process, induced by the progressive physical deterioration, which causes a consequent functional obsolescence. This process, which is generally continuous and controllable over time, is in most cases predictable and requires an effective diagnostic system that allows adequate scheduled maintenance. The need for effective structural monitoring systems has thus become increasingly evident. Both calamitous events and natural aging processes have pointed out that an adequate diagnostic system is essential to detect structural changes that could affect the performance and safety of a structure [1] [2] [3].

In recent years, the rapid development of more effective data acquisition systems and Internet of Things (IoT) architectures has focused the attention on the possibility to collect a large number of useful information from a very big amount of data, coming from the structures if properly monitored. However, there are still scarce application examples that concretely demonstrate the feasibility and power of such approaches.

Structural monitoring has not yet developed from its initial phase of research tool and “ad hoc” solution for structural troubles and faults, to become a standard approach in civil engineering.

Many other fields of engineering like aviation and automotive have adopted the use of monitoring systems during the last three decades as a standard tool.

Currently, each vehicle has an average of 60-100 sensors on board. Because cars are rapidly getting “smarter” the number of sensors is projected to reach as many as 200 sensors per car. These numbers translate to approximately 22 billion sensors used in the automotive industry per year by 2020. The global market for automotive sensors was USD 26 billion in 2016 and could be USD 43 billion in 2021 [4].

The current Airbus A350 model has a total of close to 6000 sensors across the entire plane and generates 2.5 Tb of data per day, while the newer model – expected to take to the skies in 2020 – will capture more than triple that amount [5]. Aircraft Sensors Market was worth USD 1.68 billion in 2017 and is projected to reach USD 2.36 billion by 2023 [6].

Almost no civil engineering structure, such as bridges, tunnels, dams, buildings is nowadays designed and built with a standard supply of sensors in it like planes and cars. None today will buy a car without ABS or ESP but using non monitored structures during transportation is not yet felt as a lack of safety by common opinion.

The traditional implementation of diagnostic systems for the estimation of building safety levels requires an accurate assessment of the current state of the buildings, through detailed and targeted surveys. Structural health monitoring procedures represent its own the assessment process on existing or new buildings, without the need for specific, time consuming, invasive and costly investigation on the structure.

The awareness of the advantages that could be obtained with effective monitoring systems appear to be still not widespread. The reason lies in the traditional structural monitoring systems, which are not very efficient and rather invasive due to the need to perform load tests, dynamic analyses and other in situ inspections, completed and integrated by complex numerical analyses. It follows that, if applied conventionally, monitoring can prove to be an expensive practice in economic, timing and effectiveness terms.

On the other hand, during the last decade, the evolution of low cost sensors derived from TLC industry, the development of high-speed internet communication, the birth of cloud based services and the rise of big data platforms able to apply artificial intelligence techniques, have changed the possible scenario of structural monitoring. Structural Health Monitoring (SHM) can now be deployed on large scale to infrastructures as a standard option (even since construction) and not only when specific pathologies are found [7] [8].

The main goal of large scale monitoring is obtaining continuous information on the performance level of the monitored system in order to guarantee high levels of safety and efficiency and to guide pro-active maintenance interventions in order to optimize the managing costs of an infrastructure.

This paper describes the application of low-cost sensors based on MEMS technology as part of an innovative and large-scale SHM system for infrastructure monitoring, offering a reasonably priced opportunity to build a minimally invasive permanent diagnostic system, able to provide the user with information on the health state of the structure controllable over time.

In particular, data from a real-time monitoring system installed on two studies/application examples in Italy are presented. Specific data processing algorithms have been developed in order to analyse sensor readings and provide an efficient real time monitoring. Data from sensors have been collected reliably over time and deterioration phenomena have been measured and interpreted.

2. Case studies

This paper presents the collection and interpretation of data from independent SHM systems installed by the authors and other subjects [9] on two bridges:

- a prestressed concrete bridge, built in the 60s of last century, whose deck was instrumented with clinometers in order to obtain relevant information before its demolition;
- a composite steel-concrete prestressed highway viaduct in which the external prestressing tendons are damaged by corrosion and are monitored using tri-axial accelerometers.

The following paragraphs describe the purposes of each of the presented monitoring system and the requirements they have fulfilled as well as the general system layout and a description of the technical approaches for data analysis.

3. Monitoring of the deck of prestressed concrete bridge

The highway viaduct described in this paragraph was built in the second half of the 60s of last century. It counts three central spans realized with a continuous steel beam and 7 simply supported spans 40m long on one side and 8 on the other.

The simply supported spans were made with prestressed concrete girders with 4 longitudinal double T beams connected by 5 transverse beams and a top slab. These girders were deteriorated due to age and lack of maintenance and therefore the owner of the structure decided to replace them with new steel girders.

During the first phase of demolition and replacement operations the traffic of the highway in both directions was supported by only one carriageway increasing the amount of load on the old girders.

In this phase a real-time monitoring system based on MEMS clinometers was installed on the side of the external beams of the girder as shown in figure 1.

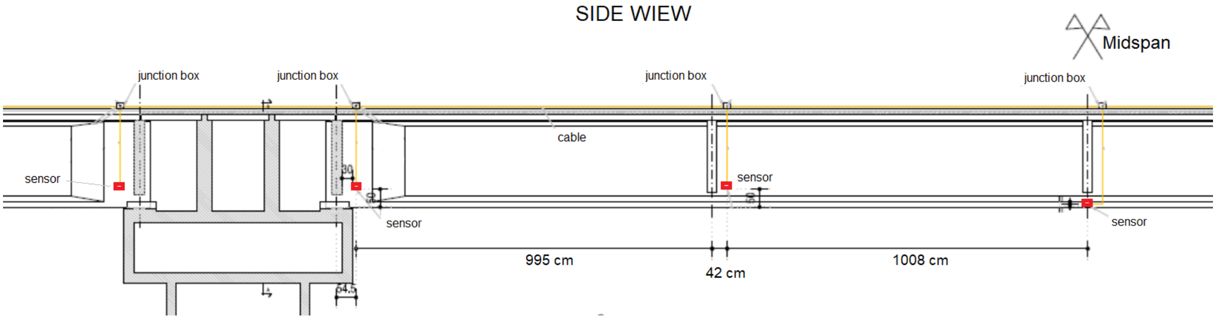

Figure 1. Side view of one half of one simply supported span

Five clinometers were installed on each span, fixed to the web of the outermost beams, for a total of 80 measuring points, 35 in the north and 40 in the south spans, respectively. Sensors are positioned at the bottom of every girder and are connected to a control unit by means of power supply cable which is also used for data transmission. Information gathered on a Raspberry is then sent to the 'Cloud' in real-time.

3.1. Methods

Each sensor is interrogated by the control unit sequentially, it acquires inclination angles with 125 Hz sampling frequency for 10 seconds, and calculates the mean value, the standard deviation, the maximum and minimum value in the 10s set. A temperature and humidity value is also acquired and tied to the set. The operation is repeated every ten minutes.

Raw data coming from the instruments have been cleaned fro temperature and humidity drifts by using a self learning regressive procedure that has allowed to estimate the values of the drifts for each sensor, which are known only within a production range, before installation.

Figure 2 shows an example of the drifts calculated for the first 35 sensors.

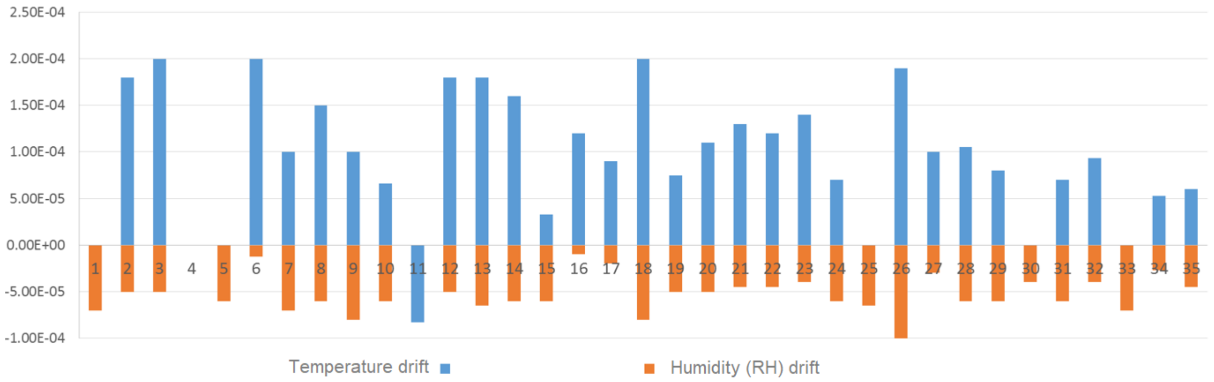

Figure 2. Temperature and humidity drifts for a group of 35 sensors

Fractiles 5% e 95% of the angle distribution within 10s of acquisition time are calculated as:

$$a_{k0.05} = a_m - 1.64\,\sigma$$
$$a_{k0.95} = a_m + 1.64\,\sigma \tag{1}$$

In order to compare the deformation values obtained by the monitoring system and the expected bridge structural behaviour, a FE model was developed. Comparison between rotations calculated by means of numerical simulation with traffic loads and the values obtained by the sensors were performed.

Using results from the FE model, threshold values have been set. At every sensor reading interval, thresholds are applied to $a_{k0.95}$ and or a_m. Three different threshold were fixed on the rotation at the bearings of the external beam of the girder:

1. **Light duty:** it represents the effect on the deck of a 40t lorry with a dynamic effect equal to 2. The obtained rotation of 1.0E-3 rad is compared to $a_{k0.95}$. This threshold can be passed many times a day during service life. The number of time this threshold is passed is simply recorded, without any warning message.
2. **Heavy duty:** it represents the effect on the deck of the SLS characteristic traffic ant thermal effect without dynamic amplification. The obtained rotation of 2.5E-3 rad is compared to $a_{k0.95}$. This threshold is chosen as an attention level as it shouldn't be passed during service life, but because of the heavy traffic on the open carriageway it can be reached in some abnormal load conditions. No damage in the deck is associated to this load level. A warning message is sent to the control room when this threshold is reached.
3. **Alarm:** Two alarm thresholds, corresponding to different scenarios.
    a. $a_{k0.95} > 1.3 * 2.50E\text{-}3$ rad = 3.25E-3 rad and consequent increase of am bigger than 5.0e-4 rad for the following 5 reading cycles.
    This scenario corresponds to the effect of an unexpected load that causes a permanent damage, like cracking or some bars failure.
    b. $a_m > 1.0E\text{-}3$ rad for at least 5 consecutive reading cycles.
    This scenario rapresents a slow deterioration of the structure (i.e. because of corrosion) without any heavy loading

3.2. Results

Figure 3 shows the first week time history of the readings obtained from one sensor positioned on the bearing of one span. The graph shows the rotations measured over time by the clinometer, compared with the first two threshold described in the previous paragraph.

The following phenomena can be evidenced:

1. mean values (green dots) are constant and close to zero. This is a positive result as the effect of the traffic does not cause any permanent deformation. This trend has been confirmed over

2 months of monitoring; weak variation of this mean value on daily or weekly basis are caused by thermal phenomena;

2. Time periods evidenced with letter A correspond to intervals when the monitoring system was shut down, because of electrical maintenance on the construction site;
3. Time periods evidenced with letter B correspond to night intervals when traffic on the bridge was closed: mean, maximum and minimum values are close together showing that the bridge is not vibrating;
4. Time periods evidenced with letter C correspond to night intervals when traffic on the bridge was open: bigger vibrations than in time B is appreciated but smaller than during daily hours between B and C where full traffic was passing on the bridge.

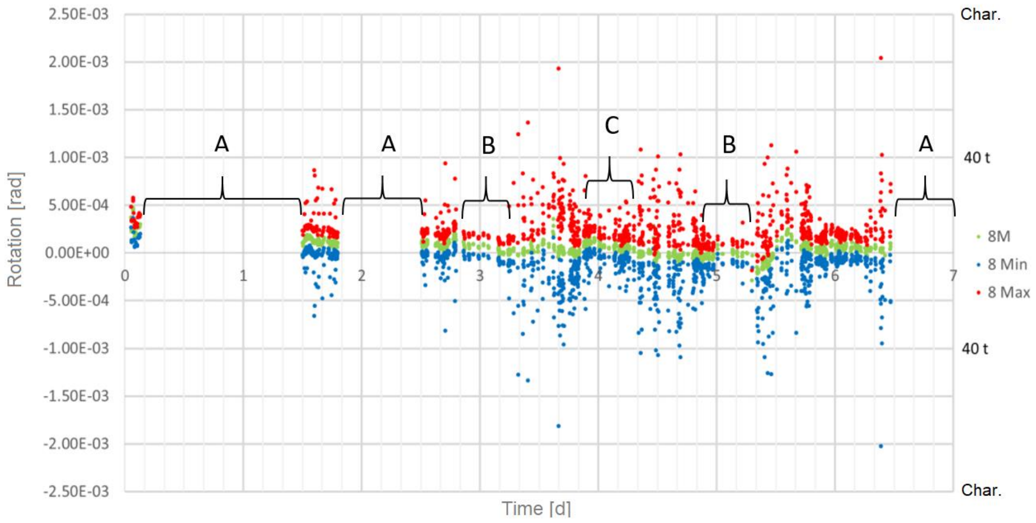

Figure 3. Results of first week of monitoring

4. Monitoring of external prestressing tendons

In last decades, bridge design with external prestressing has been largely used in civil engineering to improve concrete performances by forcing the structure to be in a state of full compression through the use of prestressing steel tendons.

The damage or failure of these elements (i.e. because of corrosion) could lead to serious consequences for the safety of the entire structure. External prestressing offers the possibility to directly inspect the tendons as in box section bridges they almost always lay inside the box section and can be periodically monitored by technicians walking inside the bridge as can be seen in figure 4 that was taken inside the bridge deck. This opportunity is not available with internal bonded prestressing, which is a much older and widespread construction technique. When some problems are detected, the inspections are typically done with 6 or 12 months scheduling e ask for the presence onsite of a task of skilled technicians. Thus, being able to assess the state of the tendons in real time remotely may grant higher safety levels for the users and a more efficient maintenance scheduling.

This paragraph will describe the application of MEMS accelerometers in a high performance and cost-effective SHM system designed for an externally prestressed bridge deck.

The bridge, opened to traffic in 2006, is a composite box girder in which the concrete webs are replaced with plane steel plates to reduce the self-weight. Mixed prestressing (internal/external) was used: internal prestressing in top slab during construction using the balanced cantilever method and external prestressing at the end of construction for continuity tendons.

The deck counts 6 spans, it is 580 m long and it is characterized by five equally spaced (120 m) hyperstatic spans and one isostatic 43m long span (see figure 5). The main girder has a cross-section height varying from 6.0 m (on the piers) to 3.0 m (in each midspan).

(a) (b)

Figure 4. (a) External steel tendons; (b) MEMS accelerometers installed on the tendons

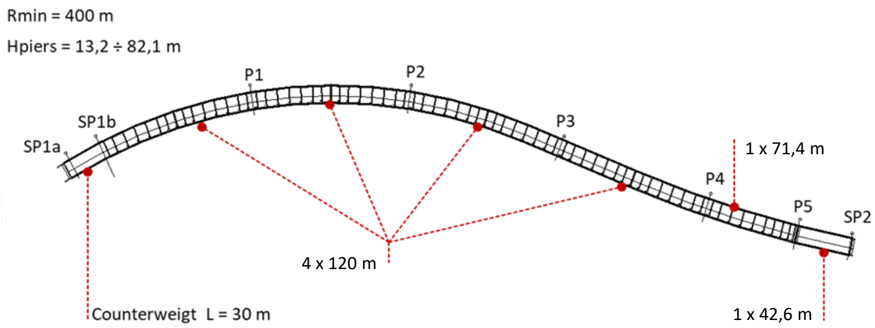

Figure 5. Plan view of the monitored highway bridge

The use of an incorrect mortar composition during grouting and the poorly execution standards of the grouting operations caused premature corrosion in several external prestressing tendons.

The installation of the monitoring system was required after the failure of one 27 strands tendon a few years after opening to traffic.

4.1. Methods

Forty-four tendons were instrumented with 88 MEMS tri-axial accelerometers, having 2 monitored sections for each tendon. The monitoring system has been working continuously for more than one year and it is described in detail in [10].

The changes in the dynamic characteristics of the monitored elements have been analysed by detecting the shift in tendons' natural frequencies. A specific data processing algorithm was developed in order to analyse the collected sensors' data and provide efficient real-time tendon monitoring [11].

Each tri-axial MEMS accelerometer provides data in the 3 orthogonal directions (x, y, z); in this way it is possible to capture the tendon vibration and deformation under traffic excitations and to obtain some dynamic parameters. Air temperature, humidity and other environmental data have been collected in order to remove the effect of these parameters: temperature turned out to be the most relevant bias.

A "standard trend" for the most relevant parameters has been obtained by combining the observations made during the first month in which the structure has been monitored. This trend allowed the definition of a benchmark of measurements corresponding to the behaviour of pre-stressing tendons subject to non-exceptional external loads.

To define threshold levels (attention / alarm) for the monitoring system, several sets of data under regular traffic excitation have been collected.

4.2. Results

Standard trends and their changes and deviations over time have been used to summarize the behaviour of the monitored structure. In particular, in the time domain, values of mean (μ), standard deviation (σ), maximum and minimum values calculated in a time window of 1s have been considered as significant control parameters and thus they have been obtained after applying a high pass filter over the signal for each measured direction (x, y and z).

Figure 6 shows the variation of the aforementioned parameters for the x, y and z directions of a sample sensor in a 24 hours' time window, the average acceleration is always close to zero, due to the periodical and almost symmetrical oscillation of the cable.

The same parameters have been calculated for several months, in order to evaluate the vibration signals trends in time. Figure 7 shows the variation of mean, 5% fractile (which corresponds to $\mu \pm 1.64\sigma$), maximum and minimum acceleration values, calculated over a 45 days period, for the x direction. A variable time window T_w of 30 minutes has been considered for the evaluation of monthly trends.

The monitoring system was also able to evidence the bridge response after two accidental actions that took place during monitoring: a small earthquake with epicentre located close to the bridge, and the failure of a second prestressing tendon.

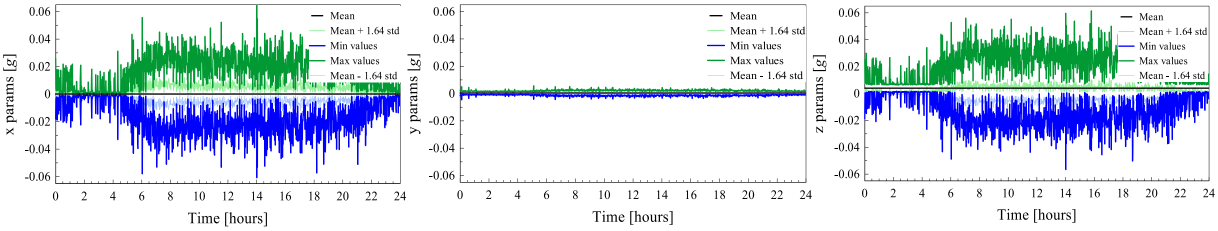

Figure 6. Daily trends calculated for the three monitored directions x, y, z – sample sensor

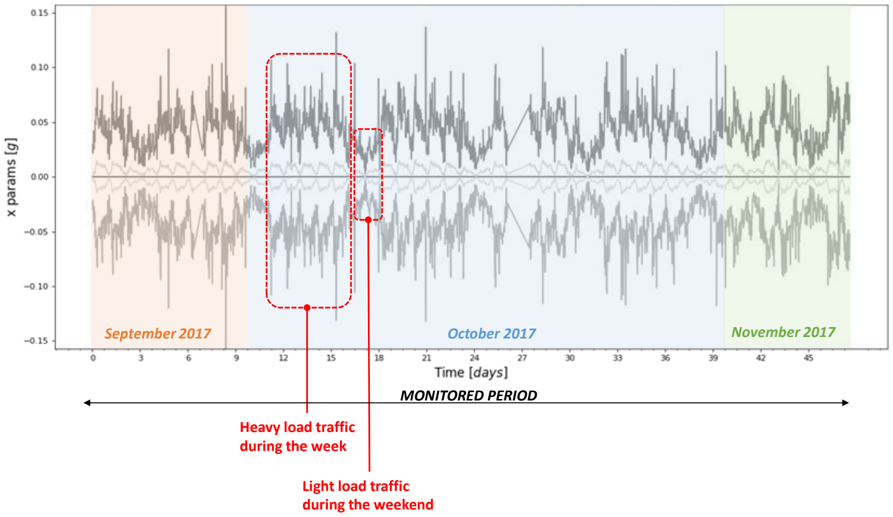

Figure 7. Monthly trend calculated for x direction – sample sensor

5. Conclusions

The monitoring of civil structures is gathering more and more attention, both for the need to check the safety of structures over time and for the undeniable advantages that can derive from a programmed maintenance [12].

This paper presents an innovative system for monitoring and diagnosing different structures, both in static and dynamic conditions. The peculiarity of the system lies in being composed of low-cost sensors based on MEMS technology, capable of monitoring various physical quantities, and linked together with different technologies for data transfer and power supply.

The recorded data are initially processed directly on the sensors and then sent to the cloud, where they are available for further processing or for a comparison with the expected reference parameters, obtained by calibrated mathematical models.

One of the most important advantages of the described system is its scalability. It is in fact possible to design both applications that involve the installation of a few sensor units as well as installations that requires the use of several hundreds or thousands of instruments.

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