Monitoring the Cathedral of Milan: An Archive with More Than 50 Years of Measurements

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Abstract. The paper describes the origin and evolution of the monitoring system of the Duomo di Milano, which was installed during the 1960s. In that period, differential movements induced by the extraction of groundwater (among other factors) caused significant instability and risk of collapse of the monument. Today, the monitoring system is still operative. Instruments, techniques, and calculation procedures were continuously updated considering the continuity of the time series, resulting in a precious archive for structural health monitoring and conservation. The actual configuration of the monitoring system includes a large variety of both automatic and manual sensors, digital and mechanical, in real-time or with an established periodicity. Moreover, the monitoring system inside the cathedral still preserves continuity with the original measurements thanks to continuous maintenance carried out over time. The manuscript illustrates and discusses the original system as well as the updates related to activities that began more than half a century ago.

Keywords: Conservation · Digital archive · Dynamic/Static monitoring · Sensor · Subsidence

1 Introduction

The Cathedral of Milan (Duomo di Milano, Fig. 1) is an imposing gothic masterpiece located in the heart of Milan. The construction began in 1386 over the ancient basilicas of Santa Maria Maggiore and Santa Tecla, whose remains are still visible in the archeological area. Veneranda Fabbrica del Duomo di Milano (VFD) is the institution founded in 1387 in charge of the completion and conservation of the Duomo. In the same year, the marble of Candoglia quarries

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O. Gervasi et al. (Eds.): ICCSA 2022, LNCS 13375, pp. 575–590, 2022.
https://doi.org/10.1007/978-3-031-10522-7_39

was made available for construction. Today, the marble is used for continuous restoration activities, which are essential for preserving the monument.

The aim of this paper is not an extensive description of the Duomo and its rich and complex history, and the reader is referred to specific textbooks, such as [1,2]. The authors intend to illustrate and discuss the origin and evolution of the monitoring system of the Cathedral, whose initial version was installed during the 1960s, and it has been continuously updated and integrated during the following decades.

Starting from the second half of the 1900s, differential movements caused by sudden variations of the water table in the city center (coupled with other factors) caused significant instability and risk of collapse of the monument.

Ferrari da Passano [3] describes the causes of instability considering both historical and constructive aspects (e.g., size and constructive methods of foundations and columns, construction of the round arches, main spire, and the three smaller spires) as well as movements induced by "modern" factors: vibrations due to vehicular traffic on three sides around the Duomo (North, East, South), the metro underground line (North), and subsidence for the rapid change in the water table.

Fig. 1. The Duomo di Milano.

The initial monitoring system allowed specialists to measure the differential vertical movements and rotations of 12 columns, mainly along a line through the transept, as well as the four columns of the tiburium [3] (Fig. 2).

Continuous upgrades were carried out to extend the system to the entire church and the surrounding area, including the square and other buildings. The evolution of the monitoring system followed the numerous restoration activities, especially during the interventions on the columns, the facade, and the main spire.

The paper describes the history of a 50-year time series of monitoring data, the integrations, and the actual multi-sensor configuration. A link between main restoration activities and the upgrade of the monitoring systems is also illustrated and discussed, along with the maintenance required to guarantee the posterity of the system.

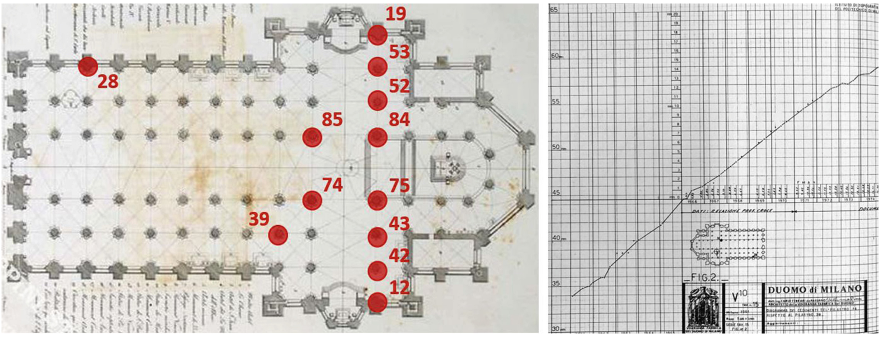

Fig. 2. The first system installed to capture vertical movements of some piers.

2 Actual Configuration of High Precision Levelling Networks for Subsidence Monitoring

2.1 The Archive of Differential Movements for Subsidence Monitoring

The actual configuration of the leveling network is the result of continuous updates in network configuration, number of points and their distribution, instruments, and processing methods.

The installation of a leveling network started in 1961 when the rapid change of the water table in the city caused differential movements of the structures of the Duomo [4]. As mentioned in the introduction, the first measurements were in the transept area. Nowadays, the internal leveling network (Fig. 3) is made up of 59 benchmarks installed on the columns. It provides a time series of vertical differential movements since 1969 that goes back to 1965 for a subset of points. The configuration and installation of the monitoring system were defined by Veneranda Fabbrica del Duomo di Milano and the Institute of Surveying, Photogrammetry, and Geophysics of Politecnico di Milano, i.e. the Polytechnic University of Milan.

Measurements are still acquired twice a year (always in May and November), notwithstanding initial data in 1965–1978 were also acquired with a higher frequency (4 seasons). The network features several closed loops, and measurements are adjusted via least squares, obtaining elevations with a precision of ±0.1 mm. As no stable benchmark is available in the area, point 39 has always been assumed as a reference since the first measurements.

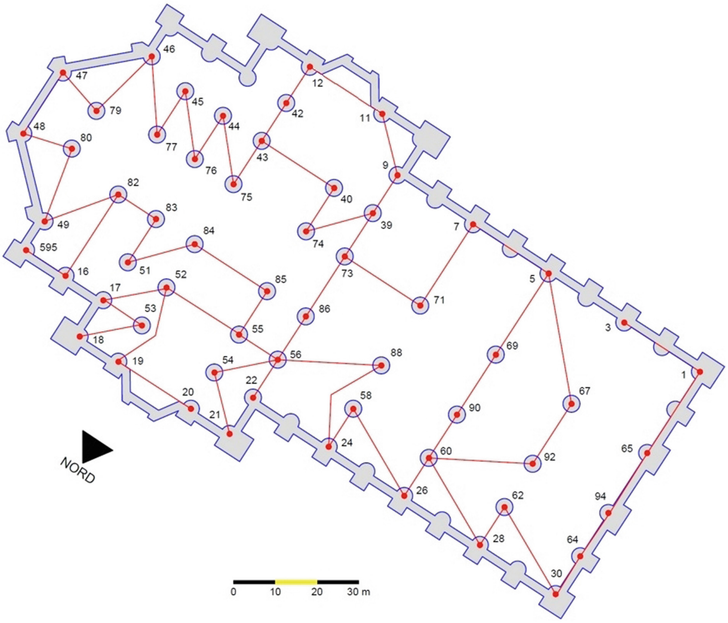

Fig. 3. The internal leveling network

Figure 4 shows a contour line representation obtained by interpolating vertical movements in the period 1970–2020 using rational basis splines, obtaining a DEM representation from which contours can be generated. As mentioned, differential movements are calculated with respect to column 39. For these reasons, columns show both positive and negative variations. The settlement of the transept is rather evident, with a maximum value reached from the middle towards the south.

An external leveling network is installed on buildings around the Duomo (Fig. 5). Points are distributed on the Cathedral, the square, and the main buildings and streets in the area (Palazzo Ducale, Galleria Vittorio Emanuele, etc.). Measurements are acquired once a year (always in May), obtaining adjusted elevations with a precision of ±0.1 mm for 92 points.

The first measurements were taken in 1966. Such measurements confirm that the maximum negative displacement is in the transept (Fig. 6). The software today used for least squares adjustment was implemented in MATLAB and allows a combined adjustment of internal and external leveling networks. It replaced a previous software implementation, which could not run the simultaneous adjustment of the two networks. Different tests carried out on smaller networks of other projects confirmed the consistency of the numerical outputs of the two software.

Recently, additional leveling benchmarks were added to the church's bell tower of S. Gottardo (2014). The aim was to include the belltower, using a

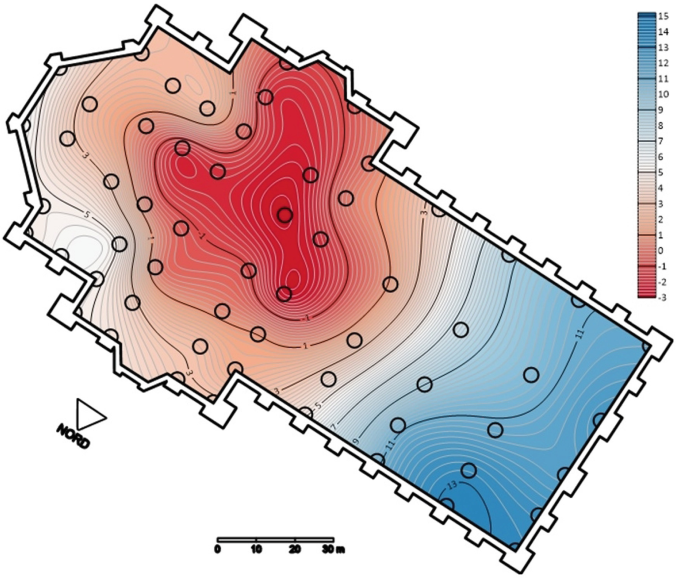

Fig. 4. Relative vertical displacements in the period 1970–2020 represented as contour lines.

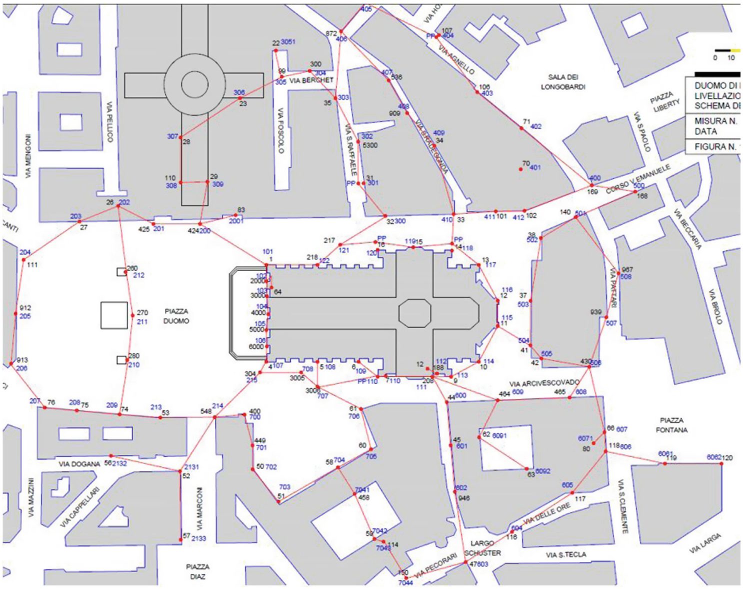

Fig. 5. Scheme of the external leveling network.

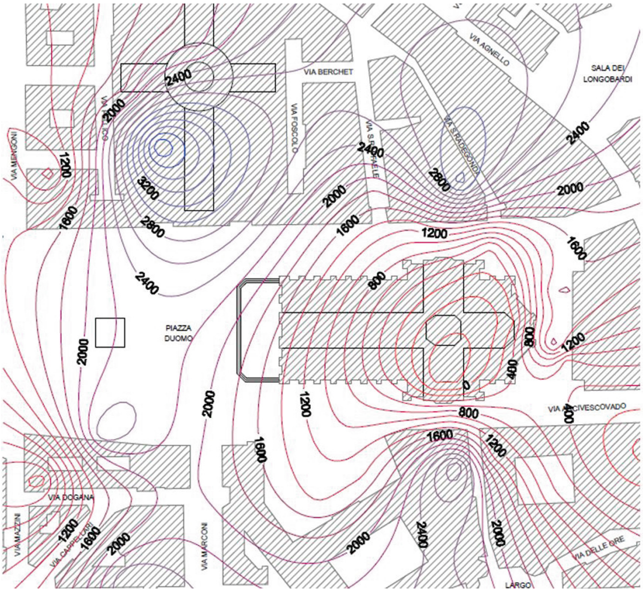

Fig. 6. Vertical movements in the square represented as contour lines (in mm/100) between 1966 and 2018.

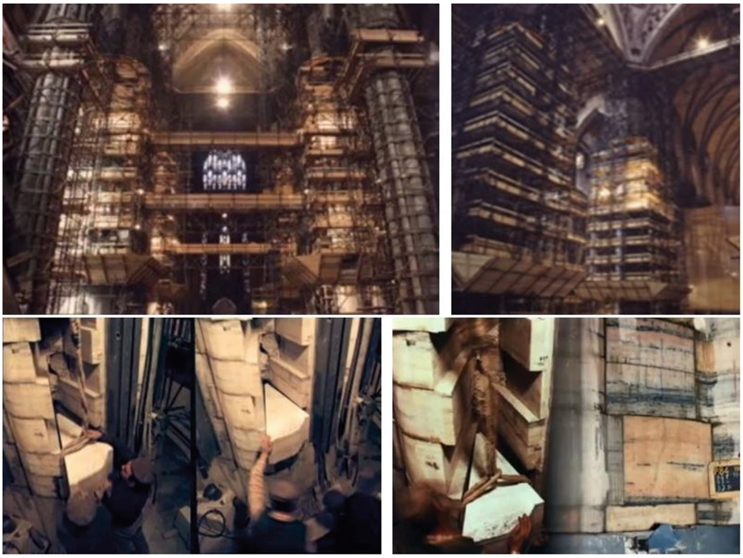

Fig. 7. The supporting structure placed around the columns during restoration.

system to detect vertical movements and rotations. As benchmarks are installed on opposite sides, the relative vertical movements also provide information about the structure's rotation.

Internal and external leveling networks allowed one to quantify the differential movements after and before major restoration works of the 4 large columns of the tiburium, which was carried out in 1981–1984 [3]. The measured vertical movements measured in that period for the 4 main columns were 1.40 mm (column n. 74), 2.12 mm (n. 75), 2.16 mm (n. 84), and 2.89 mm (n. 85). The operation entailed the replacement of damaged material equivalent to approximately thirty percent of their volume, restoring stability to the Duomo's core (Fig. 7).

A graph of the differential movements of a subset of selected piers is shown in (Fig. 8). As can be seen, variations were much more rapid in 1970–80/85.

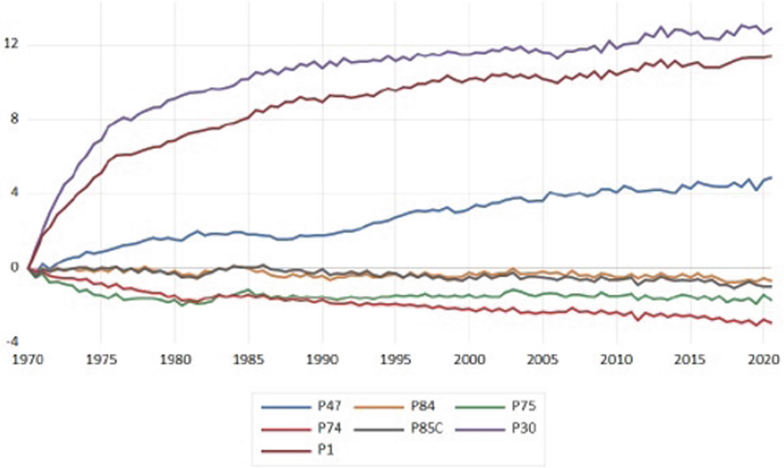

Fig. 8. Graph of differential vertical settlements (in mm) in the period 1970–2020 for a subset of columns.

2.2 Differential Vertical Movements of the Main Spire

An additional leveling network was also installed in 2008 at the bottom of the main spire called "guglia maggiore". The aim was to monitor vertical movements during the restoration work of the main spire, which required the installation of a scaffolding placed around the spire and reaching the top (Fig. 9).

Reference benchmarks are installed on two external spires (1000 and 2000), whereas point 3000 is a reference point connected to the top of the spire with an invar wire. The remaining points are installed at the base level of the tiburium. More details about the systems installed on the main spire of the Duomo (including both manual and automatic sensors and tools) are described in [5].

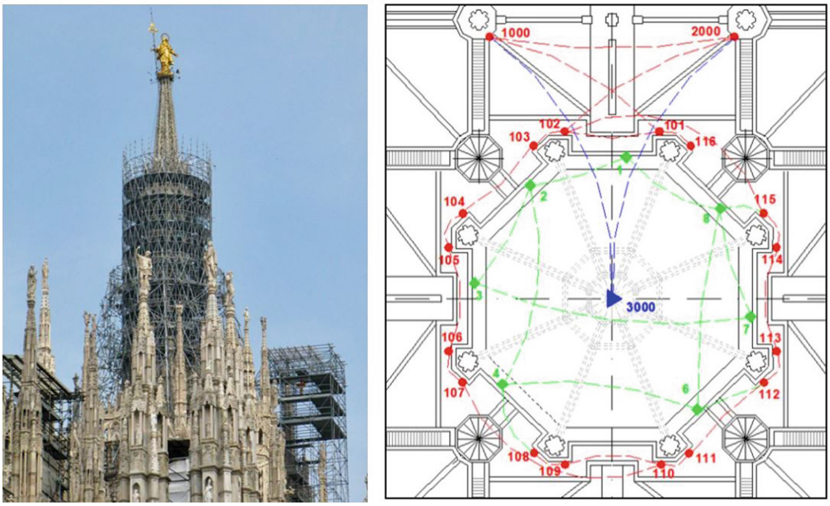

Fig. 9. The main spire and the scaffolding, and the leveling network around the base of the tiburium.

Recent restoration work of the intrados of the vault required a scaffolding that changed the geometry of the network. Today, the external loop around the tiburium is still operative, preserving the continuity of the archive. Additional points were instead added directly to the scaffolding.

Once the restoration of the vault is completed, the original scheme will be again available. This is an important consideration, which can be extended to other parts of the Cathedral currently monitored with other methods, including internal and external leveling networks. Restoration work is always required in the Cathedral, and this often requires a consequent change in the measurement strategy. All operations are always performed to preserve the time series, i.e., without removing points and protecting them if restoration activities are carried out in the area.

3 Tilt Monitoring

A tilt monitoring system was installed on several columns of the Cathedral in May 1972. Additional measurement points were added in the following years, obtaining the actual configuration shown in Fig. 10. Measurements are carried out with the manual reading of a vertical wire using the plumb bob principle. The instrument allows one to measure the variation of inclination between a point on top (where the wire is fixed) and the base of the column, where the instrument can be placed through a special plate. Variation of inclination is calculated from two readings providing the position of the wire with a precision of ±0.1 mm. The system can be removed, leaving only the wire and connection plate. It can therefore be used for the other columns.

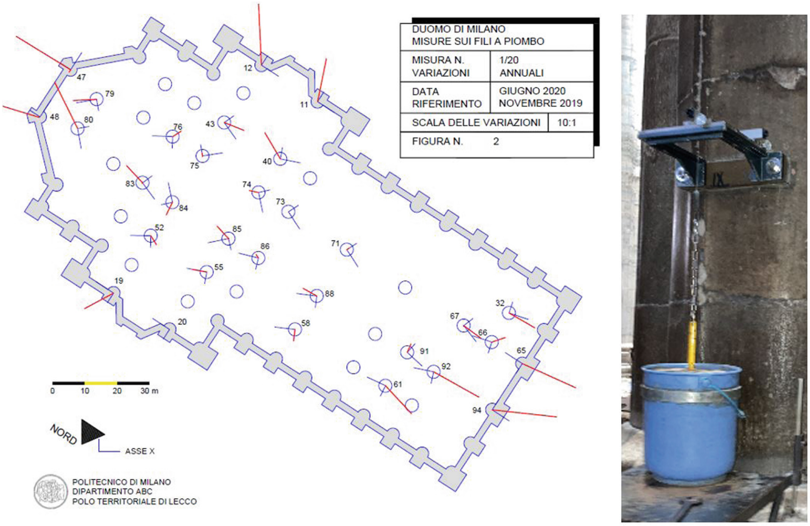

Fig. 10. Scheme of verticality variations measured with the plumbline using a 2-axis coordinatometer (precision ±0.1 mm).

Fig. 11. Measurements of tilt variations using an optical plumb installed on the façade and apse of the Duomo. The configuration on the left allows the connection of a vertical surface. The figure on the right shows the installation on a permanent reference on the floor.

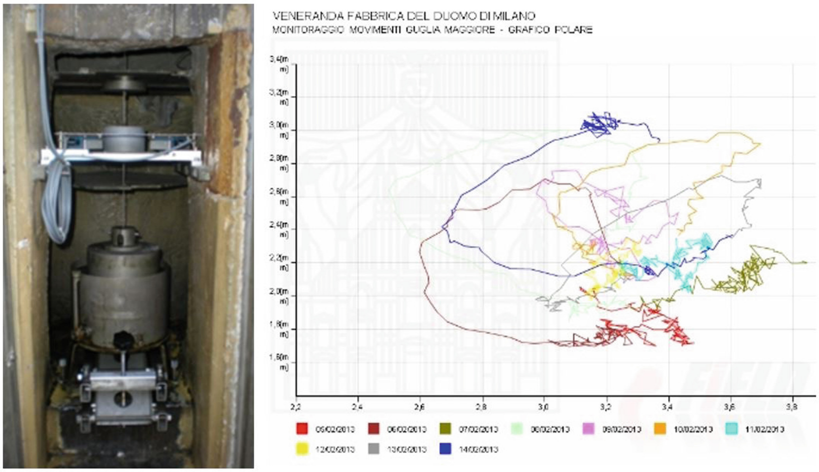

Fig. 12. The automatic plumb for verticality measurements of the spire. The figure on the right shows the movements of the spire using a polar graph representation.

Today, 32 columns are monitored. Moreover, the 4 columns of the tiburium and two columns of the façade have a double plumb system, i.e., wires connected at two different levels to check movements on top and at an intermediate level.

Measurements are carried out every 6 months, always in May and November, i.e., following the periodicity of leveling measurements. Data are reported on maps using a vector-based representation showing annual, partial, and total variations with respect to the first measurement epoch.

A different system is instead used to monitor the variation of inclination outside the Cathedral. 5 monitoring points are installed on the façade, and 2 on the columns of the apse. As the wire cannot be used outside, an optical plummet (Fig. 11) placed on a micrometric sled is used to collimate reference points and measure inclination variations.

The inclination of the spire is also monitored with an automatic plumb able to provide continuous measurements. The original system (Fig. 12) was recently renovated with a more modern sensor.

3.1 Other Monitoring Tools in the Duomo: A Short Overview

The monitoring system of the Duomo includes several other sensors and tools. Restoration activities and maintenance are a continuous process in the Cathedral and the installation of temporary solutions able to provide monitoring information has an active role in the operations. An example is the monitoring system able to capture the relative movement between the spire and the scaffolding around it with the use of GNSS technology. Figure 13 shows the configuration of the system, which has a master (reference) GNSS antenna installed on the roof, a GNSS on top of the spire (close to the Madonnina), and a third GNSS receiver on the scaffolding.

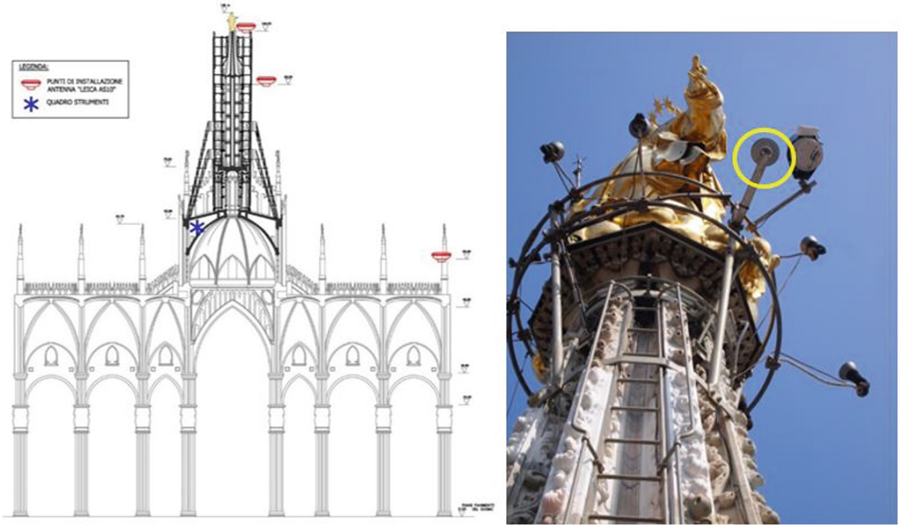

Fig. 13. Measuring in real-time the relative position between spire and scaffolding using GNSS techniques.

The system was developed to track 3D relative movements between scaffolding and spire in real-time during the restoration work of the spire, including cleaning of surfaces and replacing damaged tie rods and marble ashlars caused by iron oxidation.

In some cases, the installed sensors have become permanent and are now integrated into the archive. In other cases, continuous automatic measurements are coupled with manual measurements to verify the system itself periodically. An example is the convergence measurement of the tiburium carried out with LVDTs with an additional manual comparator with a precision of ±0.01 mm (Fig. 14). More recently, the restoration of the vault of the tiburium (currently in progress) has required the installation of temporary scaffoldings. The wires were removed so that it is possible to reposition all of them after completing restoration works.

It is worth mentioning that the monitoring system of the Cathedral includes several other sensors and tools installed in different periods to integrate the original configuration with new measurements. It is impossible to describe all the systems used and those still available in just a paper. In addition, different instruments and sensors have been tested during about 60 years of measurements, ranging from mechanical tools to digital sensors and techniques Fig. 15 shows just a selection of the previously mentioned systems. The authors intend to demonstrate that several other sensors and tools provide distance variations, 1D

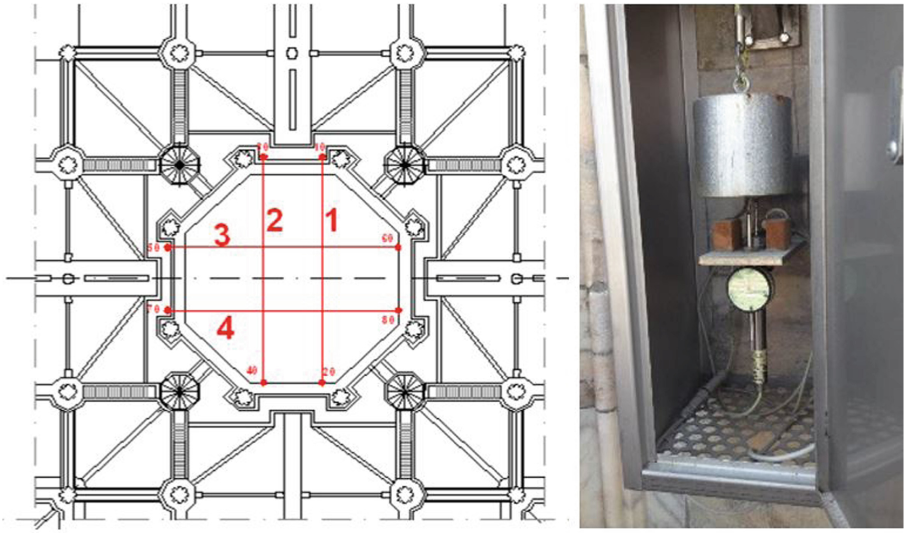

Fig. 14. LVDTs used to measure the convergence variations of the tiburium.

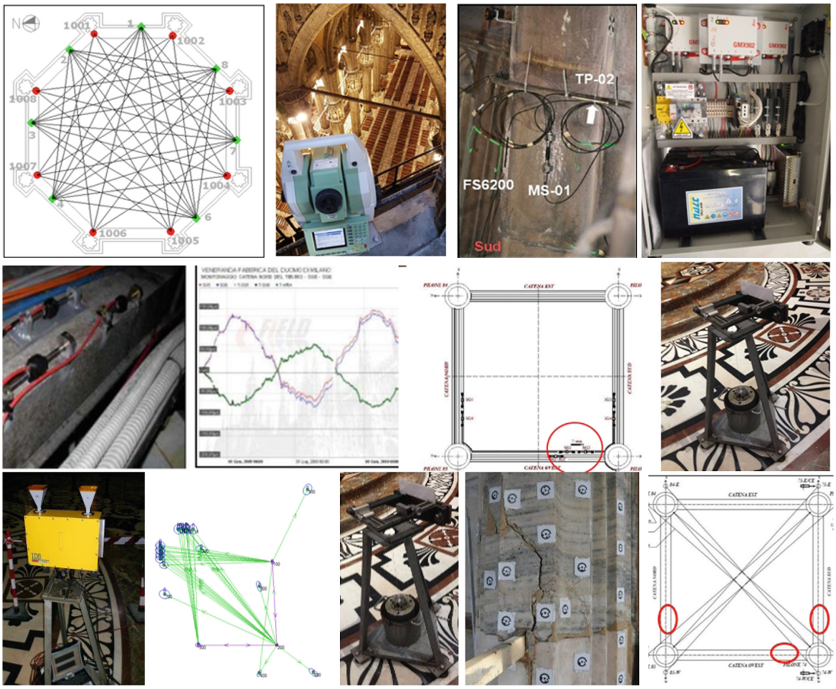

Fig. 15. Some of the monitoring sensors installed in the Cathedral of Milan. Different systems are still operative, whereas others were replaced with more modern versions.

/2D/3D displacements, crack convergence, and inclination variations, verticality deviations, among the others.

4 Continuous Monitoring

In recent years, a new continuous monitoring system was installed on the Cathedral and the spire. The system is entirely computer-based and provides an automatic transmission of the collected data, measuring 4 main types of physical quantities [6,7]:

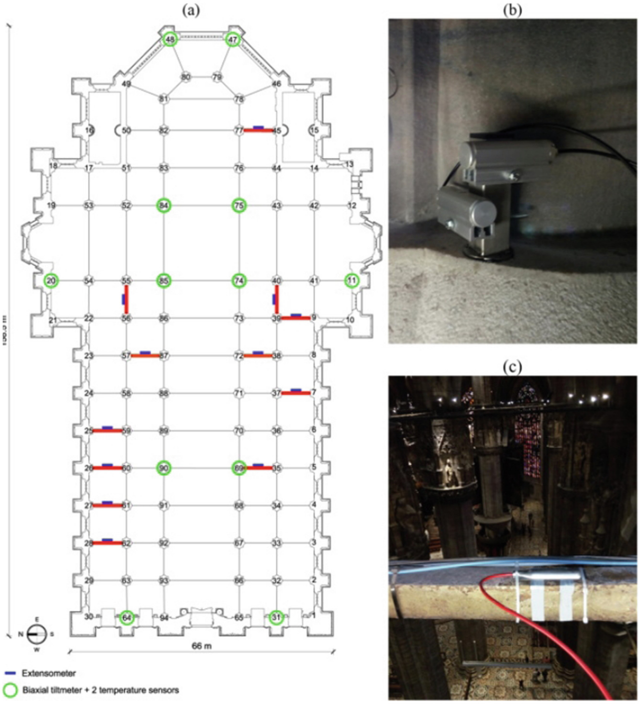

Fig. 16. (a) General layout of the static monitoring system installed in the Cathedral; (b) bi-axial tiltmeters mounted on a capital; (c) extensometer installed on a tie-rod.

- quasi-static measurements of inclination at the top of selected columns and 3 levels of the main spire;
- quasi-static strain measurements (using wireless vibrating wire extensometers) on selected tie-rods;
- measurements of internal and external environmental parameters (temperature and humidity);

- velocity measurements using electro-dynamic sensors on top of selected columns and 3 levels of the main spire.

The automatic monitoring sub-system installed on the main spire is conceptually similar to the one already used during the restoration work of the main spire [8]. Unfortunately, the system was significantly damaged by lightning strike in 2016, so that substitution was carried out with sensors featuring technical characteristics compatible with the new monitoring system.

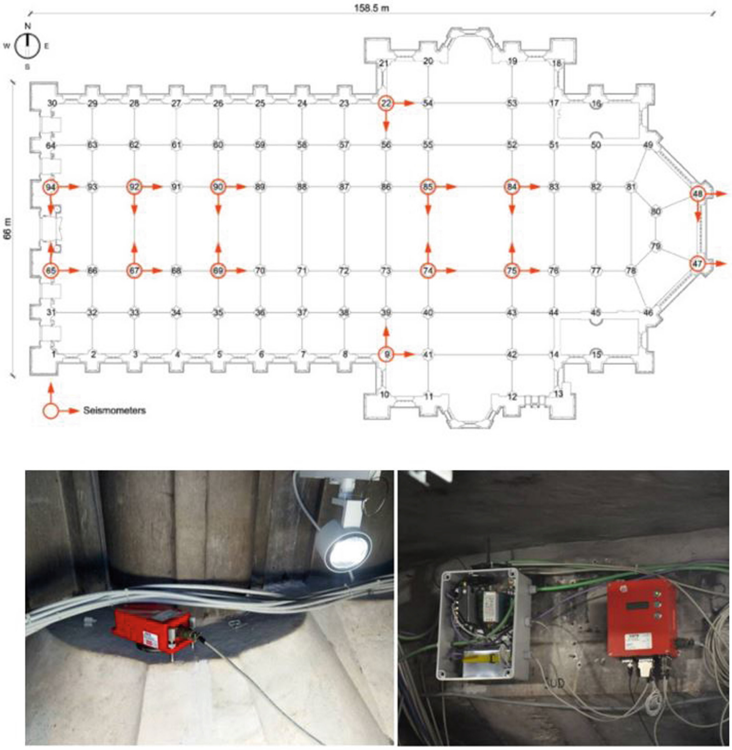

Fig. 17. General layout of the seismometers installed in the Cathedral.

The static monitoring system includes the following sensors:

- 12 bi-axial tiltmeters inside the church (Fig. 16) a and b), with ±0.5° range and ±0.5 mm/m resolution;
- 3 bi-axial tiltmeters with integrated temperature sensors installed at different levels (+65.87 m, +74.99 m, +91.67 m) of the main spire;
- 12 vibrating wire extensometers installed on 10 tie-rods;
- 12 hygrometers close to the extensometers;
- a weather station installed on the highest accessible level of the main spire (+91.67 m).

The dynamic monitoring system consists of:

- 13 biaxial seismometers and 1 mono-axial seismometer, installed at the top of selected columns inside the Cathedral (Fig. 17). They can measure the velocity in two orthogonal directions: N-S (transversal) and E-W (longitudinal);
- 3*times*3 mono-axial seismometers, installed at the same levels of the main spire together with the biaxial tiltmeters of the static monitoring system.

5 Conclusions

The monitoring system of the Duomo di Milano includes a variety of methods and has a long history. The first measurements taken in the '60 have been continuously integrated following technological advancements. Special attention has always been paid to the continuity of the time series.

The archive of leveling measurements includes more than 50 years of data. The historical archive of measurements has been restructured, offering advanced functions and tools for data visualization and processing in GIS and statistical software. The system is also integrated with a Web-GIS application able to provide rapid access to measurements.

A report with numerical data, graphs, schemes, and a description of the system and the observed movements is constantly produced and delivered every six months [9]. New sensors were installed in different years of technological advances, and local solutions are continuously developed to support minor and major interventions that are an essential part of the daily activity of Veneranda Fabbrica del Duomo.

The importance of considering past observations and guaranteeing the continuity of the archive and the integration with new sensors will continue in the collaboration between Veneranda Fabbrica del Duomo di Milano and Politecnico di Milano.

Acknowledgment. The work was carried out within the framework of the agreement between Veneranda Fabbrica del Duomo di Milano and Politecnico di Milano.

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