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Structural Health Monitoring of the Roman bridge S. Angelo on the Savuto river (Scigliano, Italy), by integration of a new sensor and geomatic techniques

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ABSTRACT
The Roman Bridge of S. Angelo, located along the road that connected Capua to Reggio Calabria (Via ab Regio ad Capuam), constitutes an important remain of Roman engineering works and is the best-preserved bridge along the road itself. Located in the middle valley of the Savuto river, this bridge is currently subject to structural monitoring by using various integrated techniques. The monitoring is carried out as part of a series of initiatives aimed at gaining in-depth knowledge and safeguarding a series of historic buildings in the same area. A new type of sensor, characterized by features not offered at the same time by those currently on the market, has been developed to aid structural and environmental monitoring. Previous surveys had been carried out with geomatic techniques; one of the products of these surveys is a 3D model of the bridge, used as input to carry out a Finite Element Modeling (FEM) analysis. The results of this FEM analysis will be compared with those obtained by the measurements carried out with the new sensor. The monitoring campaign, which has just begun, and the expected results are described and commented on. The main results obtained to date are the model of the bridge, a structural analysis and the settlements that have occurred over time as well as the creation of the new sensor.

Section: RESEARCH PAPER

Keywords: Sensor; laser scanner; structural health monitoring; finite element model

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1. INTRODUCTION

The archaeological heritage, by its nature, requires a series of interventions aimed to its deep knowledge, protection, conservation and enhancement. To pursue these objectives, various activities must be carried out, among which diagnostics and monitoring are of primary importance. Geomatics and new sensors have acquired an increasingly important role in both of these activities.

A significant part of the archaeological heritage is made up of buildings, constructions and structures which, due to their size and location, cannot be transported inside museums or protected with covers. This part of the heritage is, therefore, subject to the action of natural elements (rain, large temperature ranges, wind, floods, earthquakes), to human interventions and to the effects of human activities (e.g. pollution, vibrations due to traffic and, last but not least, global warming and climate change).

Structural health monitoring (SHM) is one of the main activities that are carried out in an increasingly widespread way for the protection and conservation of buildings, infrastructures and, in particular, cultural heritage. SHM consists of various techniques and instruments, among which geomatics is gaining importance.

Alongside the techniques of geomatics, various sensors are currently used. The possibilities offered by electronics and the growing availability of fast data processing and transmission systems have favored the production of new sensors which join traditional instruments and allow the continuous measurement of a series of physical and chemical parameters which are extremely useful for monitoring.

For SHM, the first requirement is a deep knowledge of the physical and geometric characteristics of the artefact under study.

Figure 1. Via ab Regio ad Capuam from Tabula Peutingeriana (left) and from Corpus Inscritionum Latinarum (right).

Surveys are carried out with integrated techniques that allow obtaining the georeferencing and the geometric relationships between the surveyed objects, the territory and other surrounding structures. The main result, however, is a three-dimensional model, often multi-resolution, usable by all professionals (art historians, architects, archaeologists, structural engineers) involved in the protection, conservation and restoration activities [1], [2], [3], [4]. The models and related information are used by Building Information Modeling (BIM) and Heritage Building Information Modeling (HBIM) software and included within Geographic Information Systems (GIS): this facilitates the collaboration and joint operation of experts operating in the various sectors [5], [6]. To obtain georeferencing, Global Navigation Satellite System (GNSS) receivers are used, capable of providing the positioning of points with an accuracy of a few cm, thanks to the diffusion of Continuously Operating Reference Stations (CORS) [7]. Very often, satellite receivers are used together with the instruments devoted to the surveys of the artifacts; receivers, more and more frequently, constitute accessories supplied with the instruments themselves. Total Stations (TS) are always fundamental tools for surveying both reference and detail points [8], while for more complex geometries the most used tools are Terrestrial Laser Scanners (TLS) [9]. Close Range Photogrammetry can exploit Structure from Motion (SfM) restitution techniques for the reconstruction of observed objects [10], so that drones are increasingly used. Drones had a remarkable evolution, thanks to improved ease of use, high-resolution cameras and positioning capabilities. Their use ranges from the survey of the territory to that of artefacts and details located in unreachable positions, to the survey in emergency conditions [11].

Along with the construction of detailed 3D models, TLS can be used to obtain physical characteristics of interest for both static and dynamic structural analysis [12], [13]. Remote sensing is increasingly widespread and, in particular, techniques based on land and air Synthetic Aperture Radar (SAR) allow us to obtain useful information at the level of the single building and of the territory at small and large scale [14], [15].

Once a detailed 3D model of the building under study has been obtained, it is necessary to carry out periodic measurements regarding geometric (displacements, deformations, rotations) and physical (temperature, humidity) quantities. Continuous measurements, obtained with special sensors, are increasingly used alongside periodic acquisitions. Continuous monitoring is closely linked to the possibility of data transmission and remote management of the instruments used. It is particularly important for those structures that may undergo sudden subsidence or collapse, preceded by minor symptoms. This happens to artifacts made with brick or stone masonry structures, which characterize almost all ancient buildings. Therefore, sensors capable of measuring different quantities of interest to structural engineers (crack meters, accelerometers, inclinometers, strain gauges) using optical fibres have undergone strong development [16]. Other sensors, which do not use optical fibres, are being proposed [17], [19]. The advantage of these instruments is that they do not require wiring for installation and operation; this feature makes them very interesting for use on inaccessible points and for their low cost. A new sensor has been used for the SHM of the ancient bridge covered by the present paper. The instrument is innovative as it has features that those currently on the market do not offer at the same time. It is based on newly developed hardware and software and is characterized by reduced dimensions, weight and consumption, excellent computing capabilities and low cost.

This paper describes the structural monitoring operations performed on the Roman bridge S. Angelo, through geomatic techniques and a new multiple sensor. The paper is structured as follows: section 2 contains the description of the bridge and the surrounding environment; section 3 deals with the newly developed sensor; section 4 contains the design of the current monitoring campaign and the description of the first on field operations.

2. THE S. ANGELO BRIDGE

Among the roads of the Roman period, the most important for the connection between Rome, Lucania, Bruttio and, consequently, Sicily, was the Via ab Regio ad Capuam (Figure 1), conceived and built during the 2nd century BC. [20]. This road, also called Via Popilia or Via Annia, was about 500 km long and started from Capua (where it branched off from the Via Appia) to reach Reggio Calabria. After crossing Cosentia (Cosenza), the road continued to Hipponium (Vibo Valentia), passing in the valley of the river Sabatum (Savuto) which was crossed near the statio ad flumen Sabatum.

Along the course of the Savuto river there are numerous Roman remains. Among these are three bridges, the largest of which forms the crossing near the *statio ad flumen Sabatum*.

It is the *S. Angelo* bridge, also known as the *Devil's* or *Hannibal's bridge*, in the municipality of Scigliano (Figure 2, Figure 3). The S. Angelo bridge must be placed chronologically in the Trajan-Hadrian period [20], [21].

Figure 2. The union of the point clouds of *S.Angelo* bridge.

The drawings made during the last restoration [22] describe the bridge with a supporting round arch structure, with a span of 21.50 and a width of 3.45 m. Multidisciplinary studies are currently being carried out which will have to lead to an in-depth knowledge of the structure, in order to guarantee its structural health.

The S. Angelo bridge is a structure that has the typical characteristics of many Roman bridges. The foundation slabs were made with overlapping blocks; they have a thickness of 1.5 m and a width of about 5 m. The design of the bridge is characterized by a single span, obtained with a masonry arch, made up of a double ring of blocks. The first one, set directly on the foundation slab without supporting piers, is made of square blocks of local dry limestone, starting directly from the foundation, with the springing points at slightly different levels; the second is made with two types of material: the fronts are in squared blocks used as formwork to build the concrete interior that covers the first load-bearing arch. An irregular masonry facing, similar to the opus incertum and made by using river pebbles, covers the abutments of the arch. A masonry ramp, with two lateral buttresses, characterizes the access to the bridge from the right bank of the river.

The first accurate survey of the building and the surrounding area [23] made it possible to obtain a geometrically accurate model. An estimate of the accuracy of the model can be provided by the deviations between the mesh obtained and the merging of the point clouds. In fact, despite the presence of dense

Figure 3. The S. Angelo bridge crossing the Savuto river.

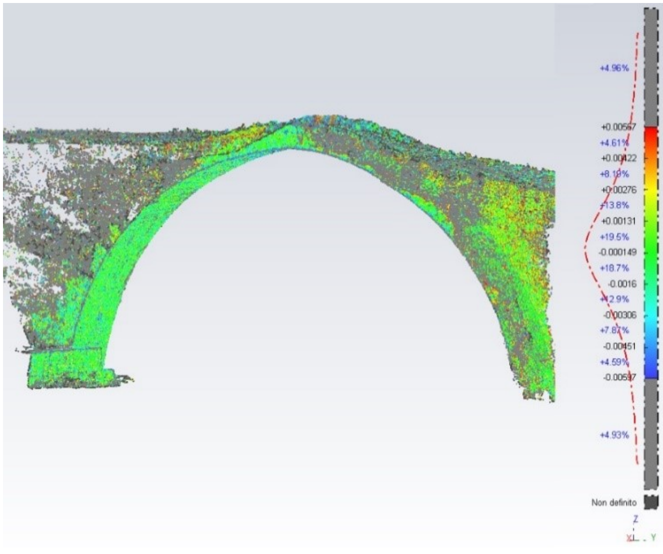

Figure 4. Differences between complete point cloud and mesh.

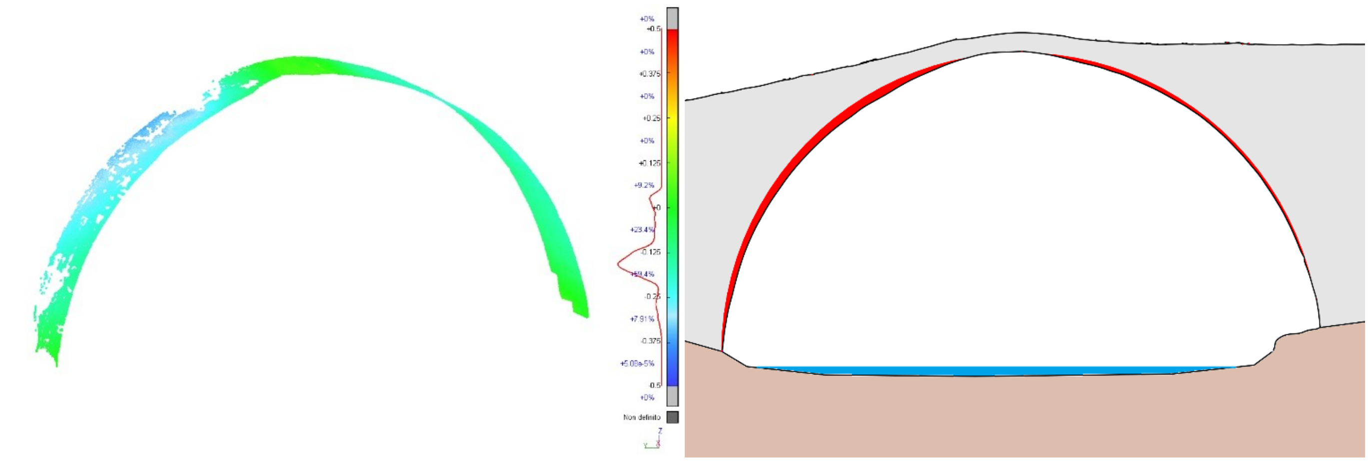

Figure 5. Differences between the ideal vault and the bridge intrados.

vegetation, the distance from the mesh is less than 6 mm for 90% of the points (Figure 4). The results of the investigation made it possible to confirm some hypotheses about the origin of the bridge. The span of the bridge is a confirmation of its Roman origins, given its value equal to 75 Roman feet, with a centimetre approximation, lower than the construction tolerances of that time. The heights of the arch springing are different on the two banks; the one corresponding to the right bank is about 1.10 m higher. An additional consideration can be made on the shape of the arch: there are two slightly lowered areas with respect to the theoretical arc of a circle.

The cause of these settlements is most likely attributed to the disassembly phase of the wooden centring which was used to lay the blocks of the dry-joint arch.

Figure 5 shows the 3D (left) and 2D (right) views of the deviations between the intrados of the most probable design arc and the mesh obtained from the TLS survey. We can observe that most of the points have a negative deviation with respect to the theoretical cylinder; this is explained by the fact that the form of the project was deduced considering the springing and the keystone of the arch as obligatory points.

The survey carried out with TLS, in addition to the 3D model of the bridge and the surrounding area, allowed the build-up of a geometric model of the supporting arch, used for the FEM structural analysis. In this way, parameters have been obtained which are useful for determining the state of structural health of the bridge. In particular, vibrational modes and natural frequencies have been achieved. Figure 6 shows the shapes of first four modes and the corresponding frequencies, which vary from 11 228 Hz for the first mode to 44 226 Hz for the fourth one.

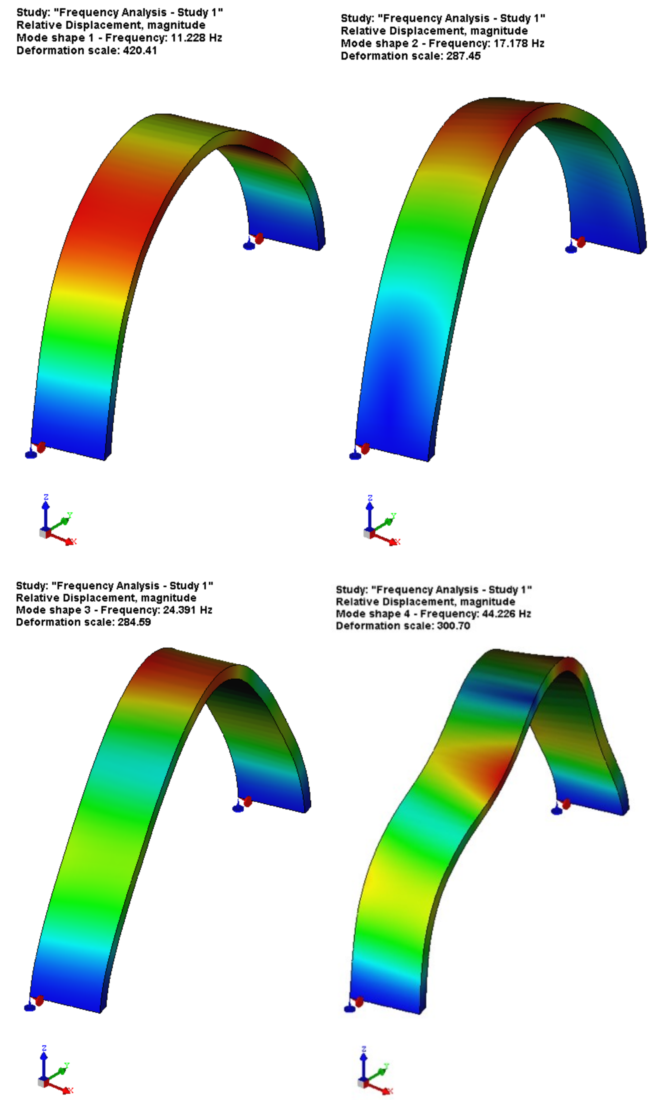

Figure 6. The first four modes of vibration of the bridge.

3. THE SENSOR POIS 2.0

POIS 2.0 is the evolution of the POIS sensor (Position and Inclination Sensor), developed a few years ago by Spring Research, a spin-off of the University of Calabria [24]. Characterized by reduced dimensions and weight, this version also differs from the first prototype in terms of reduced energy consumption. Another peculiar feature is the capability to house and manage different types of elementary sensors (environmental parameters, air quality, etc.). The core of the system is a 32-bit microcontroller which manages the acquisitions from various elementary sensors, namely: a) a 6-axis IMU sensor (IIM42652) which communicates through an I2C serial bus; b) a humidity, pressure and temperature sensor (BME688 IAQ) on I2C serial bus; c) two electrolytic inclinometer sensors which communicate through an SPI serial bus. These sensors (Fredericks Company's 0703-1602-99) provide measurements within ±25° with an accuracy of ±0.005° on one axis. Featuring DC power, they have been industrially

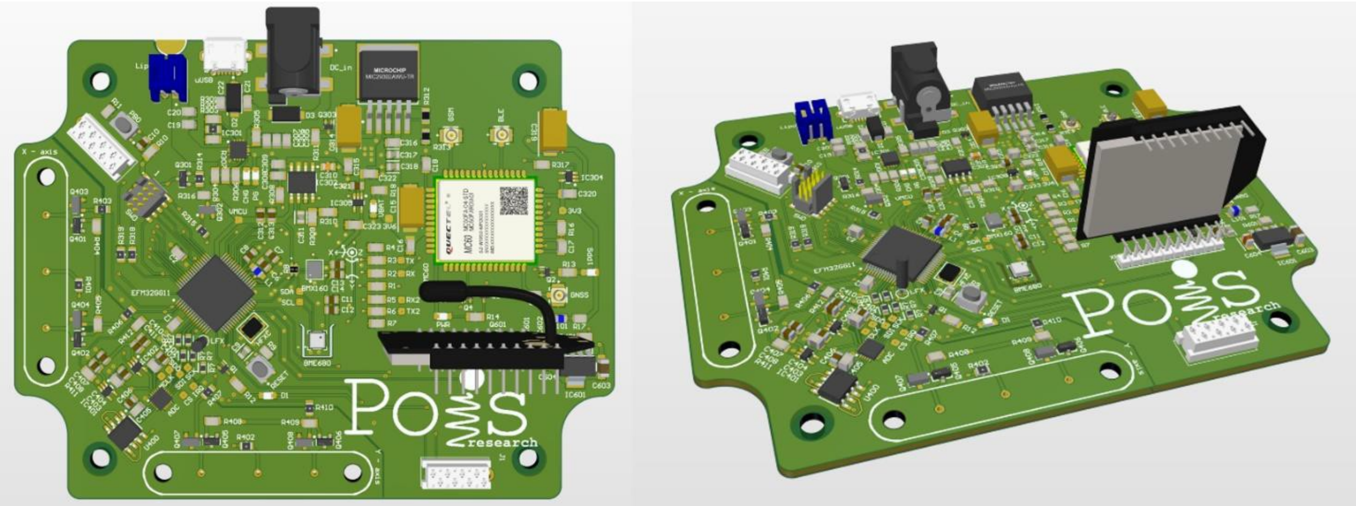

Figure 7. The POIS 2.0 multisensor card.

designed. The case is all metal and was made for use in extreme environments, thanks to the hermetic sealing.

A debug interface, equipped with a Push Button and an LED, is also managed by the microcontroller. Furthermore, POIS 2.0 holds two wireless communication devices: the Quectel MC60 module and the XBEE S2C.

The Quectel MC60 module is equipped with a Bluetooth 4.0 interface; it also contains a GNSS sensor used for geolocation. Its function is the management of bidirectional telecommunications on a quad band GSM/GPRS network, based on the exchange of MQTT packets.

For short-distance transmission and the creation of wireless local area networks, POIS 2.0 is equipped with an XBEE Pro module. It is a module widely used to set up low-cost and low-power wireless sensor networks, which guarantees the transmission of data between devices with great reliability; the module also meets IEEE 802.15.4 standards. Figure 7 shows a rendering of the electronic card with the microcontroller. The housings for the electrolytic vials are located on the left and bottom side. Figure 8 shows the main elementary sensors and the data transmission components.

POIS 2.0 was also designed to be energy self-sufficient and independent: the power supply of the POIS sensors comes only from solar panels positioned outdoors. The energy produced by the panels is conveyed through a Solar Charger Controller circuit to one or two 12V batteries which in turn power all the sensors positioned throughout the structure.

Equipped with a floating-point unit (FPU), the POIS microcontroller can perform complex mathematical operations. This allows the processing of the data acquired by the sensors directly on the board, without the need for remote post-processing. The calculation capabilities were exploited using algorithms devoted to frequency analysis of the data coming from the accelerometers. In this way, it is possible to obtain the spectrum of the oscillations that the card undergoes. POIS 2.0 is, therefore, able to carry out dynamic analyses on the acquired raw data and to obtain the natural frequencies of the structure. The results obtained can be compared to those coming from the FEM analysis of the structure model. Any variations in frequencies may be an indication of the triggering of a damage in the monitored structure. In fact, the frequency variations are the symptoms of phenomena (cracks, local subsidence, etc.) due to events that have transformed the dynamic behaviour of the structure (settling, subsidence, earthquakes).

In Figure 9 we can observe the comparison between the results obtained in the processing carried out via LABView and the POIS processor. Graphs obtained in arbitrary units were scaled to facilitate comparison. The graphs were obtained using the Z component of the acceleration to which the POIS card was subjected during a laboratory test. The Fourier transform of the data provided by POIS is compared with that obtained by LABView on the same raw data, with good accordance between the results.

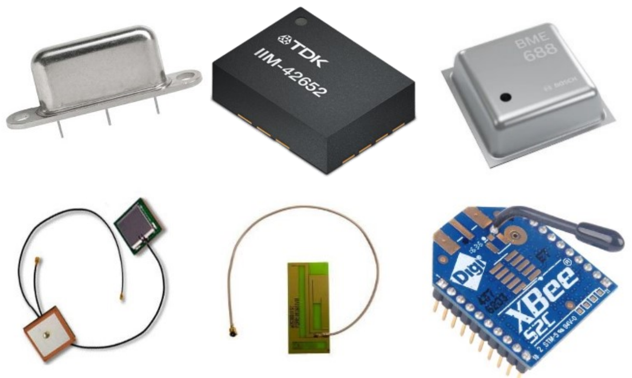

Figure 8. Components of POIS 2.0. From top-left clockwise: The electrolytic tilt sensor, the IMU sensor, the meteorological data sensor, the XBee module, the GSM/GPRS antenna, the GNSS antenna.

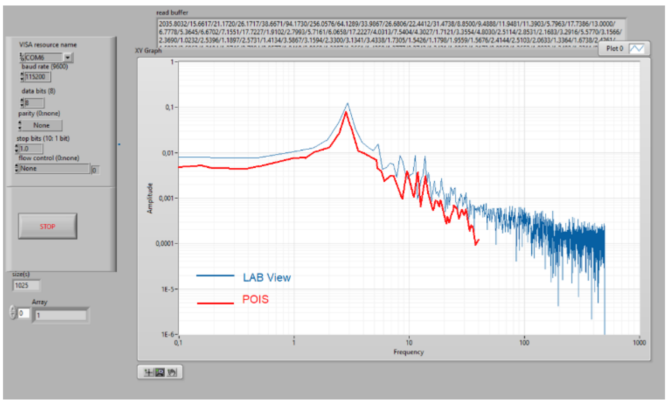

Figure 9. Frequency analysis of accelerometer data: the FFT obtained from POIS and the raw data processing via LABView are compared. For the processing of the POIS, frequencies in the range 0 – 30 Hz were considered.

4. THE MONITORING CAMPAIGN

A monitoring campaign has been designed and is being implemented in the framework of a series of activities aimed at the maintenance and protection of the bridge.

The campaign is essentially based on two types of activity: 1) the periodic execution of surveys with geomatic techniques; 2) the installation of a sensor network continuously operating and connected to an alert system [25].

For the surveys, GNSS receivers, Total Station and TLS are used. The sensors installed were POIS 2.0 in a reduced configuration: the sensors for the meteorological data and the GNSS antenna have not been implemented.

4.1 The geomatic survey

To date we have completed the first survey with geomatic techniques, which largely followed the survey carried out previously [14]. We identified some stable areas where we have chosen the reference points for the subsequent campaigns. Furthermore, a series of points to monitor on the building and in proximity were chosen. The points on the artifact partly coincide with permanently positioned sensors.

Georeferencing was carried out using dual-frequency receivers. The coordinates were obtained with the rapid-static method; for this purpose, the nearest continuous operational reference station (CORS) was used.

Figure 10 shows the layout of the geomatic survey. Red circles indicate TLS stations, yellow circles the GNSS stations, and blue circles the cylindrical targets used for the TLS point cloud registration. Two corners of old buildings have been chosen as reference; one of these (the north corner of the church of S. Michele) is highlighted in the figure with a pink circle. One can see that some points are simultaneously TLS station, GNSS point and target (Figure 11, Figure 12).

The geometric models of the bridge and the surrounding area were obtained with the TLS. A laser scanner RIEGL VZ 1000 was used, which offers the following characteristics:

Accuracy of single point:	± 8 mm
Range:	from 1 m to 1400 m
Sampling frequency:	until 122.000 points/s
Field of view: 1	100° (vertical) - 360° (horizontal)

Magnetometer
GPS receiver
Nikon D610 Camera with a 20 mm calibrated lens
Acquisition of pulse waveform return

This last feature made it possible to distinguish the vegetation from the terrain and to create, together with the bridge model, the Digital Terrain Model of the surrounding area.

The comparison of the bridge models did not reveal any detectable position differences between the homologous points chosen, confirming that in recent years the bridge has not suffered appreciable sagging or deformations. Some points of the artifact (joints between blocks of stone - points on stones present on the upper edge) were chosen to verify, with Total Station, any future displacements or deformations.

4.2. The continuous monitoring

Six POIS 2.0 sensors have been positioned on the structure of the bridge; four were fixed on the extrados, in correspondence with the keystones and about four meters away, while the other two were positioned near the springs.

Figure 13 shows the positions on the extrados where the Pois sensors have been installed. At the moment, the measures for the

Figure 10. The layout of the periodic survey.

Figure 11. GNSS receiver on a TLS station point. Three targets, circled in red, are visible.

Figure 12. The TLS on a station point. Two targets, circled in red, are visible.

Figure 13. The positioning of the POIS 2.0 sensors on the extrados of the bridge.

first month of monitoring have been acquired, which will continue for a few years.

Among the most important measurements, those of the electrolytic levels will be acquired continuously, to obtain the inclination with precision 0°.005.

Measurements are carried out every 15 minutes. The acquisition frequency can be managed remotely, so it will be possible to vary it, if necessary.

The readings of the electrolytic vials are compared with the initial one, assumed as a zero value, to obtain the variations in inclination. These will give information on rotations or settlements in the area of the structure where the sensors are positioned. The readings made by the triaxial accelerometers the Pois sensor is supplied with will also be acquired.

In the first month of monitoring, no sagging or rotations greater than the approximation of the instruments used were observed.

The trend of the observations shows greater stability of the electrolytic vials, as expected, given their greater accuracy.

Accelerometers, on the other hand, offer the possibility of carrying out measurements and their variations in real time and consequently of detecting sudden phenomena. The greater accuracy of the electrolyte levels is paid for by the slowness with which a stable measurement is obtained; they are in fact intended for the continuous measurement of inclination and its long-term variations. In this regard, we must note that the results of MEMS accelerometers are affected by temperature and suffer from a drift phenomenon. As a result, for precision measurements with MEMS, it is necessary to use expensive models.

Due to the manufact distance from roads, the sensors did not detect signals of sufficient strength to carry out a frequency analysis. For this reason, an *ad hoc* source is needed to determine the natural frequencies of the bridge.

It is therefore envisaged to carry out dynamic tests, using a vibrodyne as a source of vibration. The accelerations will be acquired. The results will be used to obtain the vibration modes and natural frequencies of the structure. The values obtained will be considered as reference values and will be compared with the output of the finite element analysis and with the results of the processing of the accelerometers data using Fourier transforms.

The comparisons of the different results will make it possible to validate and improve, on the one hand, the finite element model and, on the other, the processing algorithm developed to obtain vibration modes and frequencies using the data acquired by the POIS 2.0 sensor.

The sensor POIS 2.0, positioned on the extrados of the bridge, is shown in Figure 14, along with the sealed case of the multisensor.

An internet page has been set up for the monitoring management. Figure 15 shows the electrolytic level reading screenshot. The four boxes show: the readings of the weather station; the aerial view and georeferencing of the bridge; the scheme of the bridge with the location of the electrolytic levels; the readings of the electrolytic levels. These latter values are reported in a table that contains a column with a colour code; green indicates the normal functioning of the levels, yellow the presence of anomalous readings, red a problem in the instrumentation or the exceeding of threshold values determined when starting the monitoring. The presence of a red lecture activates an early warning.

The monitoring of an archaeological artefact through classic techniques combined with the most recent ones, the contemporary use of a new type of sensor and the development of a remotely manageable alert system constitute a novelty compared to the state of the art.

Figure 14. A POIS placed on the extrados of the bridge (left) – The sealed case of the sensor (right).

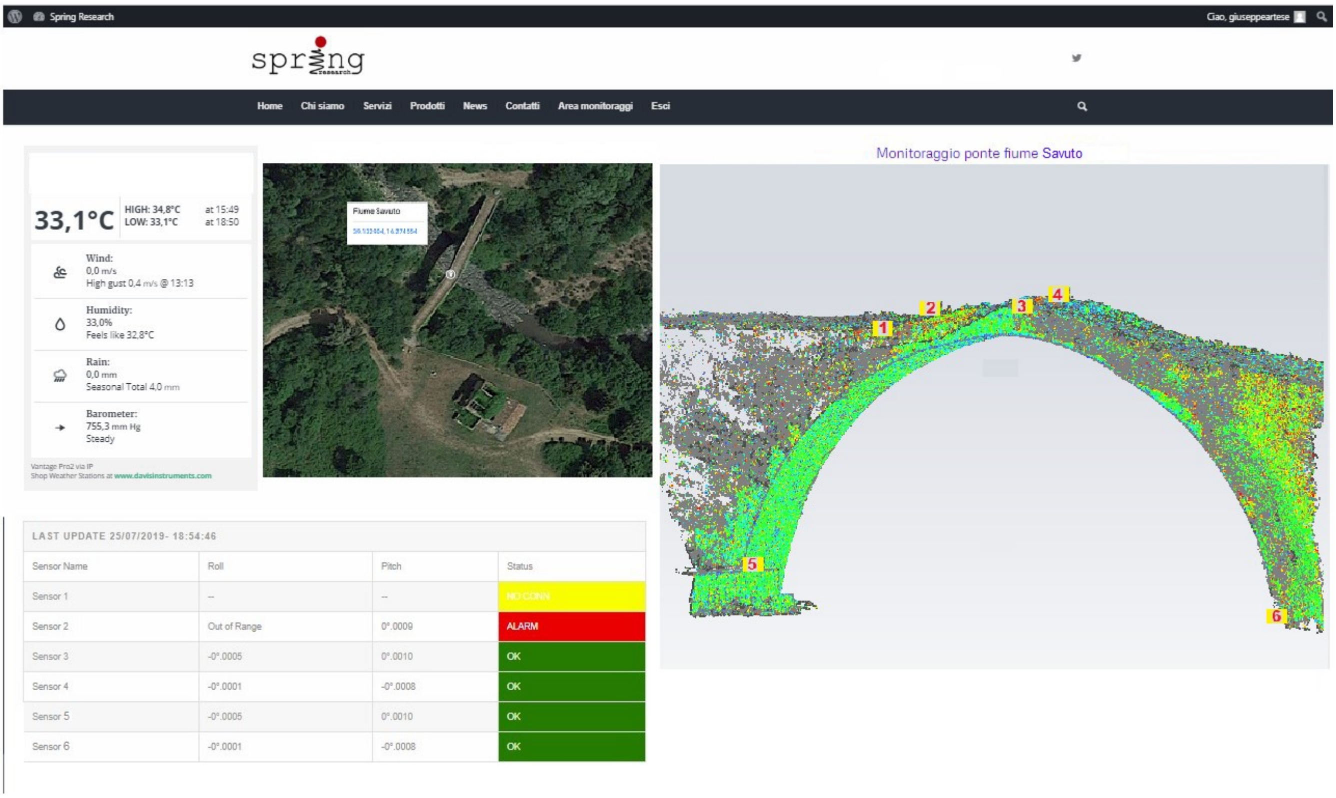

Figure 15. Screenshot of the internet page devoted to the monitoring. From top-left clockwise: a) the readings of the weather station; b) the aerial view and georeferencing of the bridge; c) the scheme of the building with the location of the electrolytic levels; d) the readings of the electrolytic levels.

5. CONCLUSIONS

The monitoring of the Roman bridge S.Angelo, over the Savuto river in Scigliano, Italy, was designed and developed using geomatic techniques and a new sensor.

The surveys conducted with GNSS and TLS allowed, in addition to geo-referencing, the development of a detailed model of the bridge, which can be used for SHM. This model has led to the determination of the natural vibration frequencies obtained with FEM analysis.

An innovative instrument has been developed, which performs functions that those currently on the market do not offer at the same time.

The new sensor, POIS 2.0, is a small hub for managing elementary sensors. In the case of the S. Angelo bridge, the readings made by the accelerometers and electrolyte levels are of particular interest. The first month of monitoring highlighted a situation of stability of the building, as there were no sagging. An internet page has been set up which allows the management of monitoring and the activation of early warnings.

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