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The integration of a new sensor and geomatic techniques for monitoring the Roman bridge *S. Angelo* on the *Savuto* river (Scigliano, Italy)

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***Abstract* – The S. Angelo Roman bridge is an important remain, along the Via ab Regio ad Capuam, a Roman road quite well preserved. The bridge, sited in the valley of the Savuto river, is subject to structural monitoring by integrated techniques. In the framework of the several activities regarding the artifact and other historic buildings, a new sensor dedicated to structural and environmental monitoring has been realized. Geomatic activities, previously carried out, had allowed to realize a 3D model useful to carry out a Finite Element Modeling analysis. The output of this FEM analysis will be compared to the data obtained by the new sensor. The monitoring campaign that has just started is presented and the expected results are described.**

I. INTRODUCTION

Diagnostics and monitoring play a primary role among the several activities devoted to the conservation, protection and valorization of archaeological heritage. Geomatics and geomatic sensors are of primary importance for performing both of the activities.

This is increasingly true in the case of artifacts made up of ancient structures, not kept inside museums, but exposed for centuries or even millennia to the action of atmospheric agents and anthropic interventions.

In a first phase, knowledge of the geometric and physical characteristics of the artefact under consideration is required. Surveys with integrated surveying techniques are therefore carried out for the purpose of georeferencing, to determine the geometric relationships between the detected objects and the surrounding structures and, last but not least, to obtain a three-dimensional model that can be used by all professionals to their respective activities (Archaeologists, historians, architects, structural engineers) [1-3]. The models and related information are included within Geographic Information Systems (GIS), Building Information Modeling (BIM) and Heritage Building Information Modeling (HBIM), in order to allow the joint operation of experts from the various sectors [4]. Georeferencing is carried out with the use of Global Navigation Satellite System (GNSS) receivers, increasingly integrated with classic Total Stations (TS) and with Terrestrial Laser Scanners (TLS). Drones, equipped with increasingly high-performance cameras and navigation and positioning systems, are used together with Structure from Motion (SfM) techniques, which make it possible to obtain useful models to integrate what is obtained from TLS, especially for areas that are not very accessible or visible [5].

In addition to providing detailed 3D models, TLS can be used to determine physical characteristics of considerable relevance for structural analyzes, both static and dynamic [6]. Remote sensing is also used in an increasingly widespread manner and techniques based on terrestrial and airborne Synthetic-aperture Radar (SAR) allow for useful information at the level of a single building or of the area of land in which it is located [7].

Together with the tools and methodologies that provide for the performing of periodically repeated measurements, it is possible to remotely manage various sensors, which can be installed on the object under study, and send data continuously, which allow accurate monitoring and, if necessary, the activation of early warning procedures. The use of these sensors is particularly suitable for those artifacts made with stone or brick masonry structures, which may be subject to sudden partial or total collapses.

The integration of the surveys carried out with geomatic techniques and by means of a new sensor of the Roman bridge S. Angelo is described below. In detail, section II concerns the artifact and its surroundings, section III describes the new sensor developed, while section IV houses the description of the monitoring campaign in progress.

II. THE S.ANGELO BRIDGE

The S.Angelo bridge is located along the *Via ab Regio ad Capuam*, an important road in Roman Italy. It connects the banks of the Savuto river and is the largest of the three bridges that cross this stream [8].

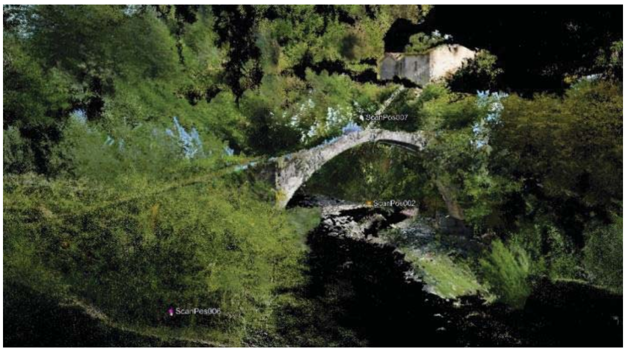

Fig. 1. The union of the point clouds of S.Angelo bridge

It is also known as the Devil's bridge or Hannibal's bridge. The bridge is currently the subject of studies with the aim of fully understanding its structure, to allow its preservation. An accurate survey, with the use of TLS, was recently performed [9]. The results confirmed the probable Roman origin of the artifact, given that the span of the round arch that characterizes it is equal to 75 Roman feet with a sub-centimeter approximation.
Among the products of the survey with TLS, in addition to a 3D model of the bridge and the surrounding area, a model of the supporting arch was obtained, which can be used for FEM element analysis. The results of the analysis provide the vibration modes and natural frequencies.

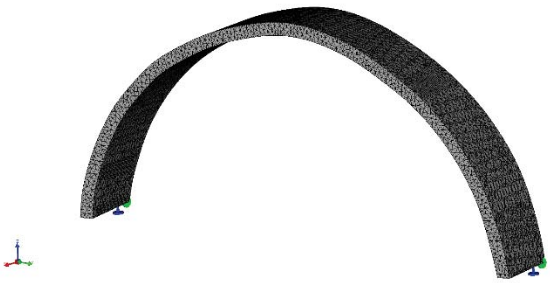

Fig. 2. The model for FEM analysis

III. THE SENSOR POIS 2.0

The POIS 2.0 Position and Inclination Sensor is the evolution of the POIS sensor, developed a few years ago by Spring Research, a spin-off of the University of Calabria [10]. Compared to the first prototype, this version is characterized by reduced dimensions and weight, lower energy consumption and allows to manage various elementary sensors (environmental parameters, air quality, etc.).
The system is managed by a 32-bit microcontroller capable of performing acquisitions from various sensors such as: IIM42652 6-axis IMU sensor, wired on I2C serial bus; b) IAQ sensor, humidity, pressure and temperature BME688 on I2C serial bus; c) Electrolytic Inclinometer Sensors (with 16bit ADC) on SPI serial bus.
The electrolytic tilt sensor used, (Fredericks Company's 0703-1602-99), provides narrow range measurement up to ± 25 ° with high accuracy of ± 0.005 ° on one axis. The design of the DC powered sensor is industrial grade, all metal, and hermetically sealed for use in extreme environments.
The microcontroller also manages a debug interface consisting of a Push Button and an LED.
In addition, the POIS card includes two wireless communication devices: the Quectel MC60 module and the XBEE S2C.
The Quectel MC60 module has a Bluetooth 4.0 interface and a GNSS interface for geolocation; it manages the telecommunications on the GSM / GPRS network in quad band for the sending and receiving of MQTT packets.
The XBEE Pro module is designed to meet IEEE 802.15.4 standards and to support the needs of low-cost, low-power wireless sensor networks by providing reliable data transmission between devices.

Fig. 3. The POIS 2.0 board

The Frequency Analysis

The microcontroller of the POIS board is equipped with a Floating Point Unit (FPU) capable of performing complex mathematical operations. Thanks to this it is possible to process the data coming from the sensors directly on the board, without the need for post-processing. Some algorithms were tested to perform the frequency analysis of the data coming from the accelerometers, thus obtaining the spectrum of the oscillations the board had been subjected to. Through the POIS 2.0 it is therefore possible not only to read the raw data acquired by the sensors but also to process them to perform dynamic analyzes.

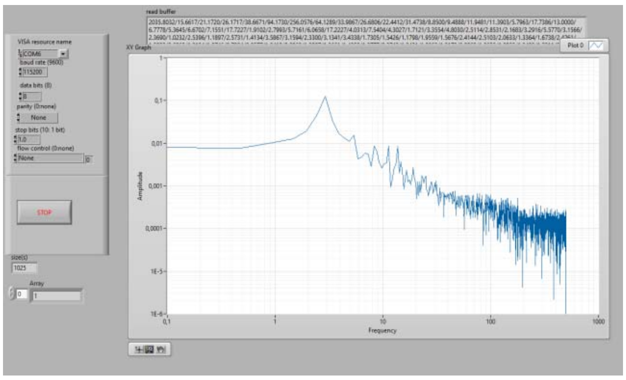

Figure 4 – Frequency analysis of accelerometer data

This feature is of particular interest if you want to monitor an artifact from a structural point of view. The frequency variations, in fact, correspond to phenomena (cracks, local failures, etc..) caused by events that have transformed the behavior of the structure (settlement, subsidence, earthquakes).

Figure 4 shows the graph, made using LABView, of the data relating to the Z component of the acceleration to which the POIS card has been subjected during a lab test. These data have been processed directly by the microcontroller present on the board, in order to visualize the spectral content of this signal through the Fourier transform. The data relating to the Fourier transform coming from the POIS card, were compared with the values obtained by LABView on the same raw data, with good agreement of the results.

IV. THE MONITORING CAMPAIGN

A monitoring campaign is launched, aimed at the maintenance and protection of the bridge. A periodic repetition of geomatic surveys is foreseen, with the use of TLS, GNSS and Total Station.

Given the purposes of monitoring, a decimeter precision is sufficient for georeferencing, while centimeter precision is required for lowering and displacements; an accuracy of 0°.005 has been chosen for the inclination.

Figure 5 – The layout of the geomatic survey.

The first geomatic survey has been completed. Reference points were identified in stable areas, as well as various points of the bridge to be monitored through periodic measurements. Georeferencing has been performed by GNSS surveying. For this aim, the closest Continuous Operating Reference Station (CORS) was used for obtaining the coordinates of the GNSS stations.

In fig. 5 the surveying layout is shown. The TLS stations are indicated with red circles, yellow circles are the GNSS stations, while the blue circles are cylindric targets used for the registration of the TLS point clouds; as reference points two edges of old buildings have been chosen, one of these is visible in the figure, represented by a pink circle. It can be seen that some points are TLS station, GNSS point and target at the same time (Figures 6, 7).

The geometry of the bridge and of the surrounding area were obtained with the use of TLS. The model obtained was compared with the one achieved with the previous survey campaign. Particular points on the artifact were considered (junctions between stone blocks - points on stones present on the upper edge). The comparison did not reveal detectable position differences between the points chosen on the two models, confirming that in recent years the bridge has not undergone any appreciable sagging or deformation.

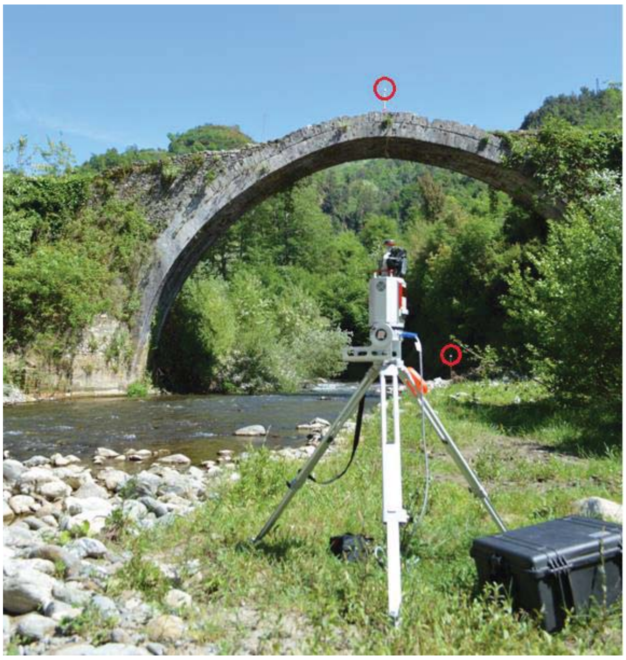

Figure 6 – A TLS station. Two targets are visible.

Figure 7 - GNSS point corresponding to a TLS station. Three TLS targets are visible.

Several POIS 2.0 sensors have be positioned on the masonry arch springings and on the extrados, near the keystone. Figure 8 shows the positions in which the Pois sensors have been installed. Measures have been acquired for the first month of the monitoring, whose duration should be several years.
The sensors will acquire the data coming, in particular, from the electrolytic vials, which allow the measurement of the inclination with 0°.005 precision.
After the implementation of the sensors, the obtained inclination value was assumed as a zero reading. For the first month of monitoring, a reading was taken every 15 minutes. The acquisition frequency, which can be managed remotely, will be modified according to the needs that arise.
The readings of the electrolytic levels were compared with the initial one to derive the variations in inclination, to be considered as an indication of rotations or subsidence of the zone of the structure where the sensor is positioned. The same readings were compared with those of the triaxial accelerometers the Pois sensor is supplied with.
In the first monitoring period, no settlements or rotations greater than the accuracy of the instrument used were observed.
The trend of the observations shows a greater stability of the electrolytic levels. The result was expected, given its greater precision.
In return, accelerometers offer the possibility to perform measurements in real time and therefore to detect sudden changes in inclinations. Electrolytic levels pay for their greater accuracy with the slowness with which a stable measurement is obtained; they are, therefore, intended for the continuous measurement of the inclination and its long-term variations. In this regard, it should be noted that MEMS accelerometers give results that depend on temperature (BIAS) and suffer from a drift phenomenon. For precision measurements with MEMS, expensive models must be used.
As regards the natural frequencies of the bridge, given the distance of the structure from roads, the sensors did not detect signals of sufficient intensity to be able to carry out a frequency analysis. There is therefore a need for an *ad hoc* source.
Thus, they will be performed dynamic tests with the use of vibrodyne. During these tests, accelerometer data will be acquired. The results will allow to obtain the vibrating modes and the natural frequencies of the structure. The values obtained, considered as a reference, will be compared with the output of the finite element analysis and with the results of the processing of accelerometric data by means of Fourier transforms.
The comparisons will allow to validate and improve, on the one hand, the finite element model and, on the other hand, the processing algorithm set up to obtain vibration modes and frequencies using the data acquired by the POIS 2.0 sensor.


Figure 8 – The positioning of Pois sensors.


Figure 9 – A Pois sensor placed in place.

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