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Environmental monitoring of *The Grotto of the Animals*: a case study for the SENNSE IoT platform

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***Abstract* – In recent years, microclimate control in cultural heritage has taken on a significant role in the protection of heritage of historical, artistic and cultural value. Since a site can be made up of different supports, the agents that intervene on the good are a combination of effects that increase the level of risk to which the good is subjected. The Grotto of the Animals, located in Florence, is the ideal case study for the SENNSE (*Spatial hEritage scieNce oNline Sensor Environment)* IoT platform designed by the National Research Council of Italy, which aims to implement advanced technologies for the damage prevention of cultural heritage subject to continuous degradation stress with irreversible effects.**

Keywords - *monitoring dashboard, preserving cultural heritage*

I. INTRODUCTION

The Grotto of the Animals, located in the garden of the Villa Medicea in Castello (Florence), is a masterpiece of Mannerism and an extraordinary example of an artificial Renaissance cave (fig.1). Commissioned by Cosimo I de' Medici in 1539, it was designed by Niccolò Tribolo and completed by Giorgio Vasari in 1580. This "water theatre" represents an allegory of power and wonder, with water games animating the sculptures of animals, including mammals, fish and crustaceans. The polychrome stones

and mosaics create a unique visual effect, evoking a living menagerie. The grotto fits harmoniously into the context of the Italian garden, considered one of the earliest examples of this style. The surroundings, with their rich botanical collection and innovative hydraulic system, reflect the Renaissance ideal of fusing art, nature and engineering. A place of extraordinary beauty and historical significance.

This place is also called "Grotto of the Flood" because of the water feature that characterized this place: visitors were surprised by tens of jets hidden among the stones in the vault and in the floor. To obtain this effect, the whole cave is surrounded by tunnels, hiding the hydraulic system and people activating the mechanisms [1].

The Grotto of the animals is an outstanding example of artificial cave, combining different artistic techniques to create a unique scenic effect. The main techniques used include:

- Mosaic and polychrome stones: the surfaces of the cave are decorated with mosaics made of coloured stones, shells and mother-of-pearl, creating a rich and vibrant visual effect.
- Sculpture: the animals, both real and imaginary, are sculpted in marble and stone. Some of them are modelled with great realism, while others present symbolic details, such as the unicorn, which represents purity.
- Water games: An innovative hydraulic system animates the cave with gushes and fountains, integrating the dynamic element of water into art.
- Naturalistic decorations: The use of natural elements such as sponges and rough stones contributes to an ambience reminiscent of a natural cave.

These techniques blend harmoniously to represent the Renaissance ideal of fusing art, nature and engineering.

This artistically beautiful place represents the ideal case study for the SENNSE (*Spatial hEritage scieNce oNline Sensor Environment)* IoT platform designed by the National Research Council of Italy. SENNSE IoT platform aims to implement advanced technologies for the damage prevention of cultural heritage.

Fig. 1 - Interior of the Grotto of the Animals

II. THE NEED FOR MONITORING

The installation of micro-environmental sensors [2] in the Grotto of the Animals represents an extraordinary opportunity to preserve this Renaissance masterpiece. A well-planned and implemented project can ensure optimal conservation while respecting the historical and artistic integrity of the site. The combination of advanced technologies and a *heritage-friendly* approach can transform the cave into a model of innovative and sustainable conservation.

Its conservation requires careful and continuous monitoring, especially when considering the installation of micro-environmental sensors to preserve this unique masterpiece. In the following paragraphs, the parameters of interest, the areas to be monitored and the specific needs and constraints of the environment are analysed.

A. Parameters of interest to be monitored

Temperature and relative humidity: These parameters are fundamental to maintain a stable microclimate inside the cave. Excessive fluctuations can cause damage to the decorative materials, such as mosaics and sculptures, favouring the formation of mold or the disintegration of surfaces. Thermal variations, especially if sudden, cause materials to expand and contract, generating mechanical stresses that can compromise the structural integrity of the work. This effect is particularly evident in composite systems, such as mosaics, where materials with different thermal expansion coefficients (e.g. stone, glass, mortar) react unevenly, promoting the formation of micro-fractures and the detachment of tiles.

Relative humidity, on the other hand, acts both as a carrier of chemical agents and as a catalyst for biological processes. In environments with high humidity, porous materials tend to absorb water, promoting the migration and crystallisation of soluble salts present in the substrate or coming from external sources. Pressure exerted by crystallised salts in the pores of the material can cause surface disintegration. In particular, it is one of the most destructive mechanisms: once deposited in the pores of the material, the salts exert internal pressures that lead to surface disintegration and loss of material. Excessively low humidity can also be harmful, causing drying and shrinkage in organic or hygroscopic materials, with consequent formation of cracks.

Fig.2 - LTE modem placed outside in waterproof box.

Concentration of CO_2 and other gases: air quality is crucial, especially in the presence of visitors. A high concentration of carbon dioxide can accelerate the deterioration of materials. Although carbon dioxide is a gas naturally present in the atmosphere, it can reach high concentrations in urban or confined environments. When CO_2 combines with atmospheric humidity, carbonic acid (H_2CO_3) is formed, a weakly acidic solution that can react with calcareous materials such as marble, travertine, sandstone and lime-based mortars. This chemical process leads to the dissolution of calcium carbonate ($CaCO_3$), the main component of many stone surfaces, causing:

- Surface erosion
- Loss of decorative details
- Formation of black crusts and altered patinas

Other gases, such as carbon monoxide, may indicate problems with the outdoor environment.

Brightness: Light, both natural and artificial, can degrade sensitive materials, such as the pigments used in mosaics. Monitoring light intensity is essential to prevent long-term damage.

Vibrations: Vibrations, caused by human activities or natural events, can compromise the structural stability of the cave. Specific sensors can detect imperceptible but potentially damaging movements.

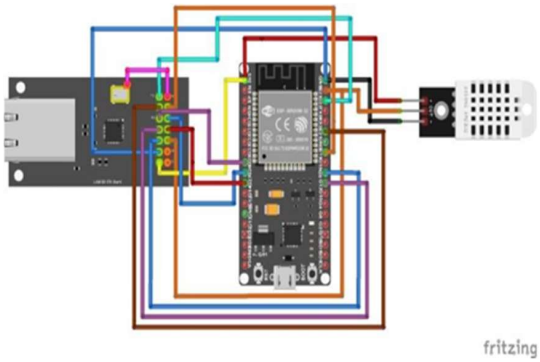

Fig.3 - Schematic of the full node.

Water residuals: It becomes of central importance to monitor the drying process of residual water on the ground after water games, for this purpose monitoring systems based on the use of thermal imaging cameras will be installed.

Cracks and fractures: Above the Grotto of the Animals is a winter garden, and the growth of the constituent plants has allowed the roots to open up large cracks and fractures within. In this case, the use of strain gauge sensors will help monitoring the state of the cracks and the speed at which they expand, allowing appropriate action to be taken in time.

B. Areas to be monitored:

Decorative surfaces: Areas covered with mosaics, polychrome stones and sculptures are particularly vulnerable to climatic variations, wear and tear, as well as the three large tubs with animal sculptures inside. Those tubs feature multicolored animals and mythological beasts like lions, giraffes, ibex, unicorns and fishes.

Sensors placed near these surfaces can provide useful data for their preservation.

Plumbing system: The pipes and fountains that feed the water features must be monitored to ensure optimal functioning and prevent structural damage.

Entrances and transit areas: These areas are subject to increased impact due to the presence of visitors. Sensors in these areas can help assess the influence of human traffic on the indoor microclimate.

Vaults and walls: The architectural structures of the cave, including vaults and walls, should be monitored for water inlet, cracks or other signs of deterioration.

Wetlands: Areas where water is most present, such as ponds and fountains, require special attention to prevent the formation of algae or mineral deposits.

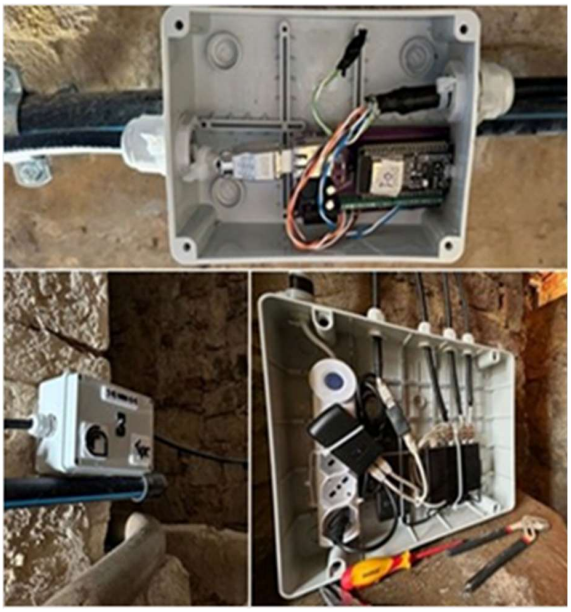

Fig.4 - Details of the nodes and POE control unit inside the ip65 waterproof boxes.

III. DESIGNING THE SYSTEM

The case study on the "Grotto of the Animals" was acquired by the SENNSE platform, born from the H2IOSC project [3] which aims to create a federated cluster of research infrastructures (RIs) in the domain of Cultural Heritage at the national level in Italy; SENNSE is a hardware/software platform for the monitoring and preservation of cultural heritage assets through the acquisition and subsequent analysis of multiple data feeds acquired from a large-scale sensor network.

An initial installation of a sensor network was carried out in February 2025 and took place by placing a system of three nodes on site that acquires data from temperature and humidity sensors located in the three tubs in the cave. The initial installation gave rise to a number of issues, first and foremost that of connectivity, which was completely absent.

And since the purpose of the installation is to send data to the platform for study and conservation purposes, the entire system cannot work without the presence, wired or not, of a stable internet connection. After an initial inspection, it was found that a strong and stable LTE radio signal was present, so it was decided to adopt this type of transmission by placing an LTE modem outside the cave (fig.2).

For the implementation of nodes controlling the sensors, ESP32 MCU boards were used and equipped with ethernet upgrade, while three DHT22 type sensors were chosen for temperature and humidity detection (fig.3), which are sturdy enough to withstand the high humidity in the

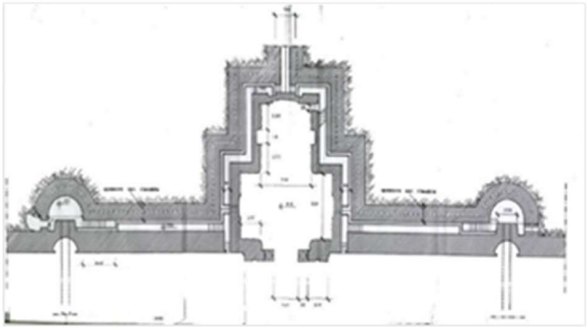

Fig.5- Plan of the cave and the narrow corridor behind it.

monitored locations.

To solve the problem of energy supply, the only source of electricity is outside the cave, the entire system was equipped with POE (Power Over Ethernet) technology, so it was possible to set up the installation with only one large cable running inside the corridors behind the cave (fig.4 and fig.5).

Due to the presence of mice in the places housing the sensor nodes, all wiring was done with professional rodent-proof cable.

The external LTE modem, the control unit, the sensor nodes and all the sensors are contained in watertight boxes that guarantee optimum efficiency and storage in an environment with particularly high humidity levels (fig.2 and fig.4).

IV. THE SENNSE DASHBOARD

In the following fig.6, an example of application of the SENNSE platform is shown. It is possible to appreciate the collection of information displayed through the dashboard relating to the installation campaign that took place in February 2025.

In general, this section of the platform allows you to manage data coming from different contexts being monitored, setting alert rules in case the parameters do not respect the set thresholds.

V. CONCLUSIONS

The Grotto of the Animals is a demonstration of the ingenuity of the Renaissance age, which combines art, nature and architecture in a unique masterpiece. However, its beauty and historical significance call for careful conservation. A preventive approach necessarily focuses on the connections between the protected object and its context [4].

The use of micro-environmental sensors ensures that this unique historic site is protected from damage caused by time. By monitoring temperature, humidity, air quality, vibration and structural integrity, researchers and conservators can preserve the cave without compromising its historical authenticity. The integration of advanced technologies, through platforms such as SENNSE,

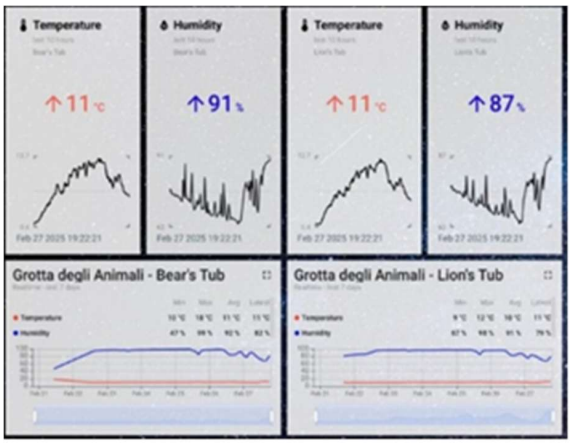

Fig.6 - Example of monitoring dashboard for the animal cave.

exemplifies the synergy between tradition and innovation, creating a model for sustainable heritage conservation. Through a careful conservation process, with full respect of the historical and artistic integrity of the site, future generations will continue to admire its wonders, just as visitors did centuries ago. Ultimately, the Grotto of the Animals is more than just an architectural marvel: it is a living example of how the Renaissance tried to harmonize human creativity with the forces of nature.

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