Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 21 (2011) 446 – 456

Procedia Engineering

www.elsevier.com/locate/procedia

2011 International Conference on Green Buildings and Sustainable Cities

Sustainability in civil engineering: integrated mix of some non-invasive sensing techniques for conservation and restoration of historical buildings and frescoes

Filiberto Lembo[a], Francesco Paolo R. Marino[a*], Nicola Ambrosecchia[b]

[a]*University of Basilicata, Viale dell'Ateneo Lucano 10, Potenza 85100, Italy*
[b]*Logos Innovazione Scrl , Matera 75100, Italy*

Abstract

Santa Maria of the Palomba Sanctuary was built in XV[th] century on a pre-existing medieval crypt, situated in a splendid landscape, on the south facing ravine on which stands the city of Matera, integrating in a wonderful way the underground and *sub divo* building; in the ages shortly following a notable cycle of frescoes was painted renewing the decorative state of the underground church.
Over many years, the building fell into decay, the structures and frescoes were flooded and damaged; so that from 1980 important restoration works were carried out, constructing ventilation canals under the floor of the hypogeic church, incorporating heating pipes, connected to solar thermal panels in such a way to secure the optimum thermo-hygrometric conditions for conservation. After almost thirty years, before working on the restoration of the frescoes it was necessary to completely and objectively characterize the existing physical conditions.

Selection and/or peer-review under responsibility of APAAS

Keywords: Semi-underground buildings, sustainability, non-invasive sensing, architecture vs energy saving

1 Introduction

In the planning environment, both in the field of Public Works and in the private sector, it has been noted, in recent years, the need to extend the knowledge of environmental and structural monitoring, aimed at the preservation, restoration, and more generally to the intervention of property and infrastructure. The monitoring of physical parameters in the interior of buildings, particularly those in

* Corresponding author. Tel.: +39-329-360-6215; fax: +39-971-205-185
E-mail addresses: francesco.marino@unibas.it

restricted conservation areas (churches, historic buildings, building complexes of environmental and cultural value), provides the elements for the planning of the restoration, while the monitoring of the structures, to be implemented in the medium-term, will provide the basis for the preliminary propaedeutic study of the design of structural strengthening and the identification of the specific intervention.

The objective of this research was particularly ambitious: to operate the simultaneous use, combined with the most highly innovative technology, to monitor the indoor rock complex of Santa Maria of the Palomba Sanctuary to control and define the actions of recovery and restoration of the frescoes.

An integrated mix of some non-invasive sensing techniques has been used:

- internal and external survey of the Sanctuary, using *laser scanner 3D*, in *WebGIS* environment, so as to specify, in particular, both the dimensional data of non accessible parts (thickness of rock-bank, morphology and position of fracture lines), and the consistency and state of conservation of the frescoes;
- thermo-hygrometrical sensing of surfaces, using infrared thermography, during a two week time frame, corresponding to a period of turbulent stormy weather in order to establish the relationship between atmospheric variations and changes in the conditions of surfaces;
- continuous monitoring of surface conditions, by means of thermo-hygrometrical and temperature surveys;
- continuous sensing of operating temperature, by means of a globothermometer.

All of these tools were linked to a network with a data logger, and the information was transmitted using the internet to a computer located in a remote centralised office.

The remote integrated survey system proved highly reliable, allowing the development of very important operations and analysis:

- to georeference all data relating to mapping and monitoring;
- to manage a great deal of information, very articulate, in an homogeneous way;
- to rationally manage measurements carried out using *laser scanner 3D*, and to show them in an interactive way or by means of cartography base with geometrical and stratigraphical drawings;
- to perform in dynamic way, on an algorithmic base, a series of functions, visualisation interrogation, analysis, control and verification of the data collected, in order to obtain the information required for planning the restoration and management of heritage sites.

2. The research

The research covered the complex of rock churches of Santa Maria of the Palomba's Sanctuary (see Fig.1). It was built in the XVth century on a pre-existing medieval crypt, situated in a splendid landscape, on the south facing ravine on which stands the city of Matera, integrating in a wonderful way the underground and *sub divo* building. It is the archetype of a building that has been stratified by hundreds of years and a great number of interventions, with the symbiosis of carved and built architecture, that characterizes the architectural charm of Matera.

It is a building complex of extreme morphological richness, which is very difficult to be analysed by means of traditional survey techniques; highly stereometric, poorly described by traditional modes of representation in plan, elevation and section, in which the components follow cadences changing point by point, in relation to the fact that they are excavated or constructed (see Fig.2). The amalgamation of several churches, very singular in typology, with single aisle and particularly enhanced in height, that, at the junction of the presbytery, create a central plan structure with semi-spherical dome on octagonal drum and horn angles, reminiscent of more classical Roman building traditions, and even more developed in height. The Sanctuary is embedded in the ridge of the ravine, whose side face, decorated with thin pilasters and arches, makes it difficult to know whether it has been escavated or constructed, and it is likely to be a combination of both.

In the ages shortly following a notable cycle of frescoes were painted renewing the decorative state of the underground church. Over many years, the building fell into decay, the structures and frescoes were flooded and damaged [1] [2]; so that from 1980 important restoration works were carried out, constructing ventilation canals under the floor of the hypogeic church, incorporating heating pipes, connected to solar thermal panels, in such a way to secure the optimum thermo-hygrometric conditions for conservation [3] (see Fig.3).

Fig. 1. (a) Photo of the Sanctuary in its context; (b) Plan of the principal level of St. Maria of the Palomba's Sanctuaty; (c) Elevation of the façade of partly *sub divo* Church

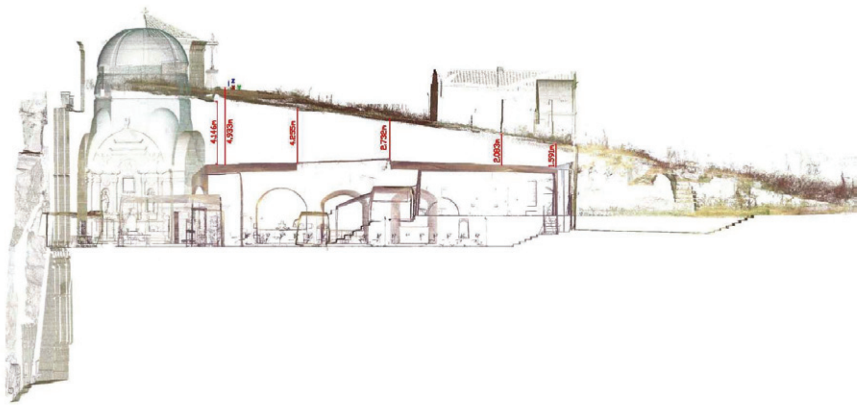

Fig. 2. Section through partly *sub divo* Church (to the left), and rock Church (to the right)

After almost thirty years, before working on the restoration of the frescoes, it was necessary to completely and objectively characterize the existing physical conditions. All of this, in the context of the extreme difficulty of treatment, has provided an excellent opportunity to try out technologies and non-invasive methods, repeatable in delicate and complex areas, also in terms of operational difficulties (lack of networks, limited accessibility), which are designed to allow the subsequent implementation and repetition of investigations, iterative and retrospective, with very low costs.

First of all, the detailed survey was carried out using 3D laser scanner [4], making it possible to appreciate the smallest details, and in analytical terms, the large plano-volumetric and morphological complexity of the building, both from the inside and the outside, defining the thickness of material placed in the most inaccessible places, their grain, texture and colour [5] (see Fig.4). This type of survey is one of the main tools for hypothesizing the construction methods of the various parts of the sanctuary and the diachronic sequence of its realization. What has now emerged is that the *sub divo* building is designed with sophistication worthy of a cultured creator, a connoisseur of styles from countries north of the Alps, a good structural designer, that possibly could be identified, and that is certainly not *quidam de populo*.

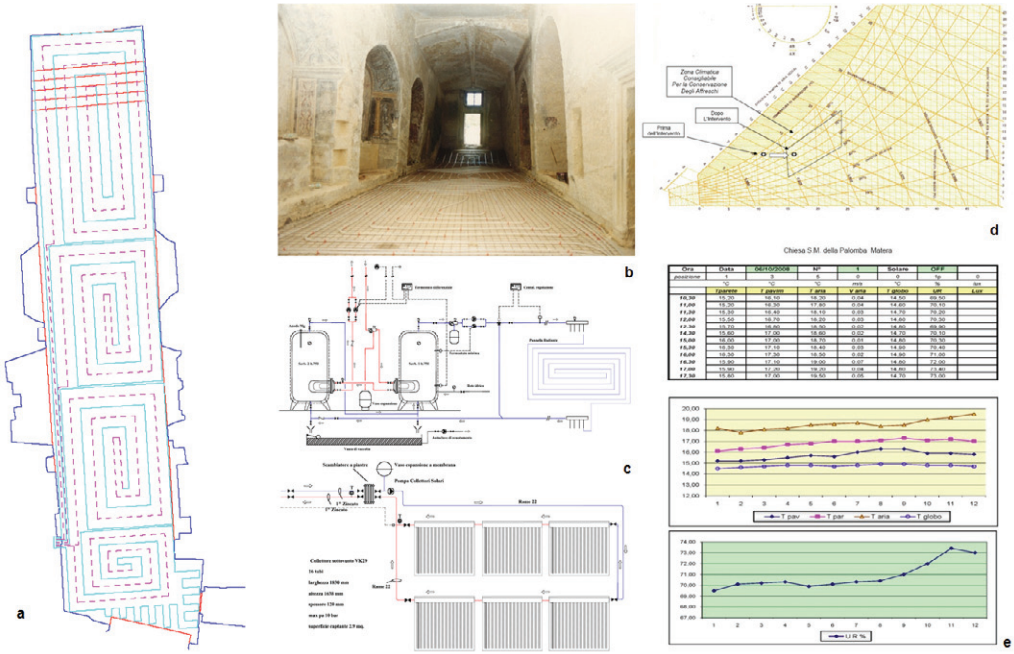

Fig. 3. (a) Serpentine of heating plant in the floor of the rock Church; (b) the interior of the rock Church, during the works in 1980; (c) working pattern of heating plant, from solar collectors to serpentine in floor; (d) Mollier diagram; (e) survey of microclimatic conditions of the rock Church

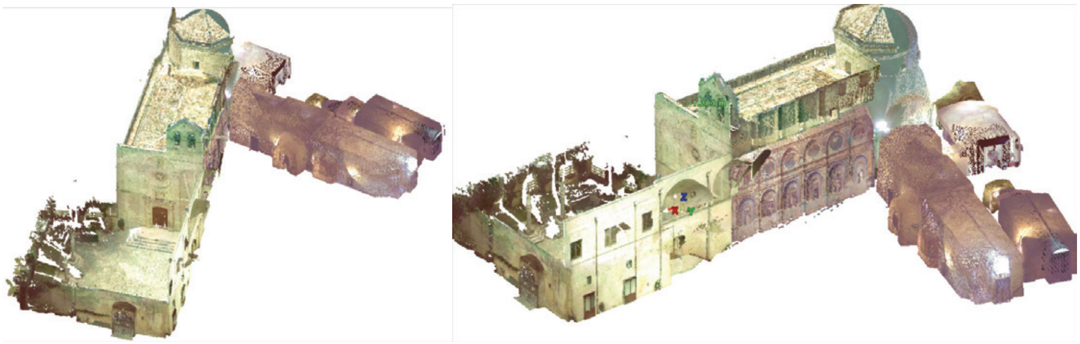

Fig. 4. Axonometric views of underground and *sub divo* buildings of St. Maria of the Palomba's sanctuary

The stereometric digital pad helped to identify the position of a tectonic fault line, that crookedly crosses the rock church. Along this fault line there are not, at present, particular thermohygrometric phenomena (see Fig.5).

The thermographic analysis case study of the fresco, superimposed on the digital model of the survey, ascertained that there are no thermal, humidity and material discontinuity across the surface, and that there has been no millimetric displacement of the wet outline on the fresco [6].

The examination was performed under normal (see Fig.6) and forced conditions, after thermal conditioning of the part subject to measurement (see Fig.7).

The process to artificially and uniformly, as much as was possible, heat the surface of the case study fresco, was carried out with the intention of surveying the distribution of the surface moisture: the temperature reached in each surface element depends strongly on the moisture content locally present, and since the temperature rise is less in more humid zones than in the drier ones, the thermographic recording allowing thus the reach of a comparative mapping of the surface moisture (see Fig.8).

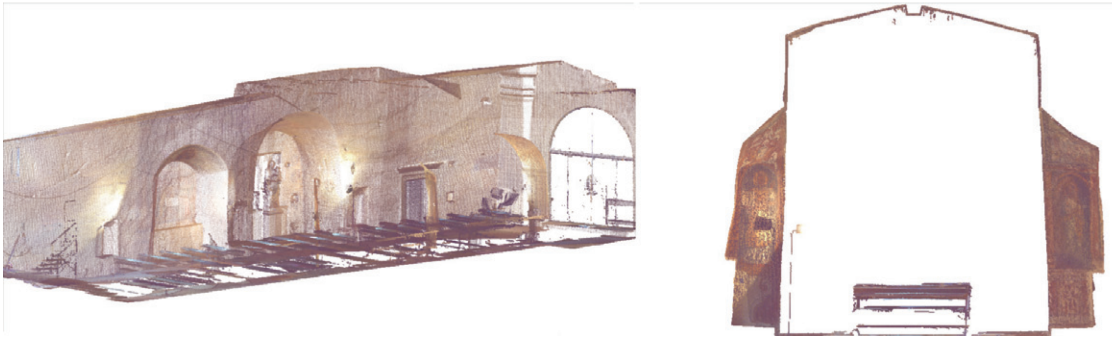

Fig. 5. Axonometric views of underground and *sub divo* buildings of St. Maria of the Palomba's sanctuary

Fig. 6. Picture of the case study fresco

Fig. 7. Conditioning of case study fresco

Furthermore, the evaporation process in the damp walls is strongly influenced by the different concentration of water between the wall and air, that is the gradient of relative humidity of the air in contact with the surface. For this reason, in addition to the water content in the masonry, the environmental variables that affect the value of this gradient were also controlled.

Hence, to integrate the measurements made with sensors in contact with the station microclimate

"Babuc A" multi-data acquisition, compared to the ambient air temperature and relative humidity, to the temperature and humidity of the air in contact with the surface, to the ventilation and possible sources of external heating (see Figg.9-10), it has also worked by thermografic means with the aim to determine the

possible evaporative flux, through the identification of the presence of areas affected by the cooling caused by the evaporation process.

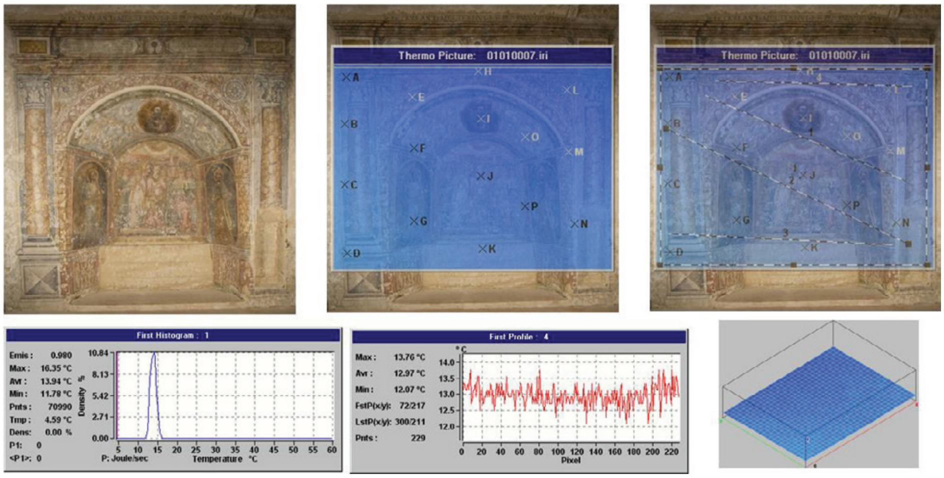

Fig. 8. Thermo picture of case study fresco and thermal analysis

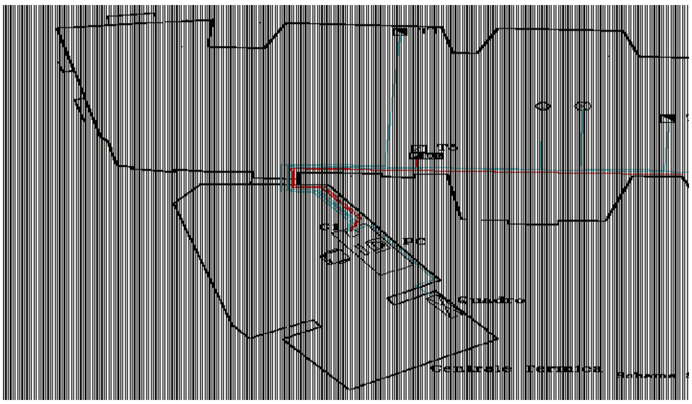

Fig. 9. Plan of rock Church and location of sensors

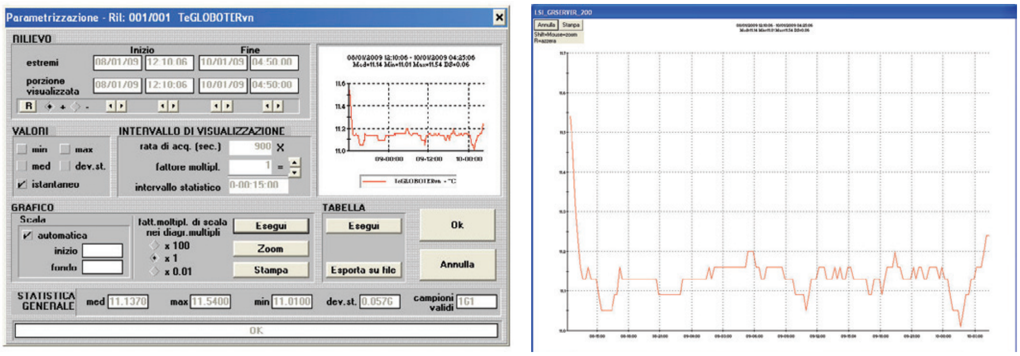

Fig. 10. (a) Records of analysis and (b) records of operating temperature of the Church, made with globothermometer

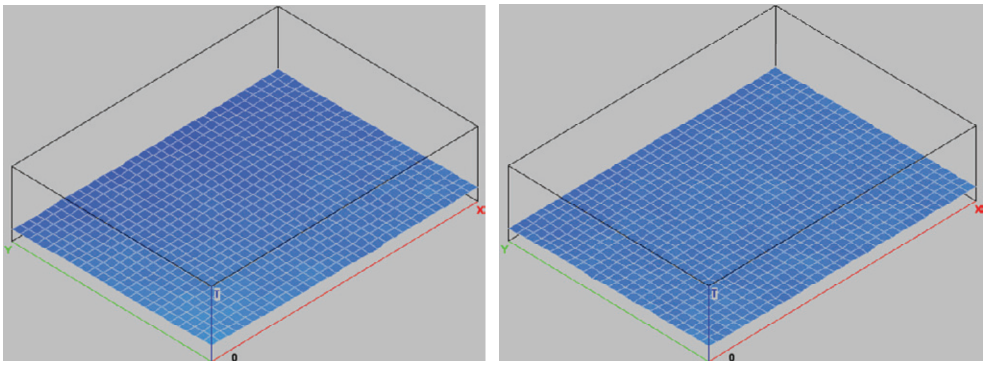

Fig. 11. (a) 3D mapping of thermographic survey "A"; (b) 3D mapping of thermographic survey "B"

The passage of water from the wall to the air determines the change of status from liquid to vapor. The energy associated with this transformation can reach values of about 100 W/m^2 : a significant value if compared to other energy exchange processes that occur on a wall surface. Thermography, as a tool for diagnostic imaging, allows the mapping of areas subject to evaporation and to evaluate areas of increased flow. In fact, in thermal images are clearly identified areas colder than where evaporation is negligible under the same conditions of heat exchange. The magnitude of this cooling can vary from a few tenths of a degree to more than ten degrees, depending on the characteristics of the material. Finally, the development of an appropriate model for the energy balance of the wall surface can provide, starting from a measurement of the temperature, a quantitative indication of the evaporation taking place, depending on the temperature of the air, the surface radiation, the relative environmental humidity and ventilation.

The range of temperatures measured in the sampling phase showed almost constant temperature, as there is minimal deviation point of the survey conducted, with detours along the temperature profiles of the survey "A" tested at 1.87, 1.45, 1.66 and 1.42 °C, and equal to 1.46, 1.87, 2.06 and 1.70 °C along the temperature profiles of the investigation "B" (see Fig.11).

The absence of areas clearly identifiable and at lower temperatures near to that of the dew, and the lack of significant temperature gradients, allowing the exclusion of the presence of damp and evaporative processes in place: it was not feasible to map areas subject to evaporation or to evaluate those of increased flow. In fact, in the infrared images shown below are not precisely identifiable areas colder than those in which both the presence of moisture that the presence of evaporation is negligible, under the same conditions of heat exchange.

Moreover, despite having tried to heat evenly and uniformly the area under investigation, the statement of the areas during cooling resulted in a detour of a few tenths of a temperature degree, which leads to exclude the presence of different concentrations of water in the internal of the wall and between wall and air, that is the gradient of relative humidity of air in contact with the surface.

Similarly, there has not been detected phenomena due to leakage or runoff of water, or pathologies caused by rising damp. Also, there are no obvious cracks or noticeable injuries of calcarenitic bench, that is substantially compact, at least in the area under investigation, namely that the area behind the fresco case study. This is demonstrated, *inter alia*, by the absolute value of the measured surface temperatures that, despite a change in the external temperature of about 5°C in the two collection periods, are substantially similar, testifying to the good thermal inertia determined by calcarenitic envelope.

The detection of temperature and humidity values, made by sensors located near the fresco, in the surrounding environment and in the outer, has provided data that were sent, via the *web server*, to a station that allows to return in real-time representation in the Mollier diagram of the condition of the environment.

Diagnostic tools and sensors used for this analysis and data collection in the field have generated a wealth of information relating to thermo-hygrometric characteristics of the structure under study allowing, on a particular area of the rock construction, the mapping of potential imbalances, through the measurement of thermal infrared thermography, and building a database for the development of a microclimate remote monitoring system through a psychometric survey.

The use of an application *WebGis* allowed to:

- obtain all georeferencing data for the mapping and monitoring;
- manage a large amount of structured and heterogeneous informations;
- rational organize the checks and display it on a base mapping and stratigraphic and geometric survey by 3D laser scanner [7] [8] (see Fig.12);
- manage display capabilities, query, analysis, control and verification of data collected in the field, in a dynamic way, based on scientific of algorithms.

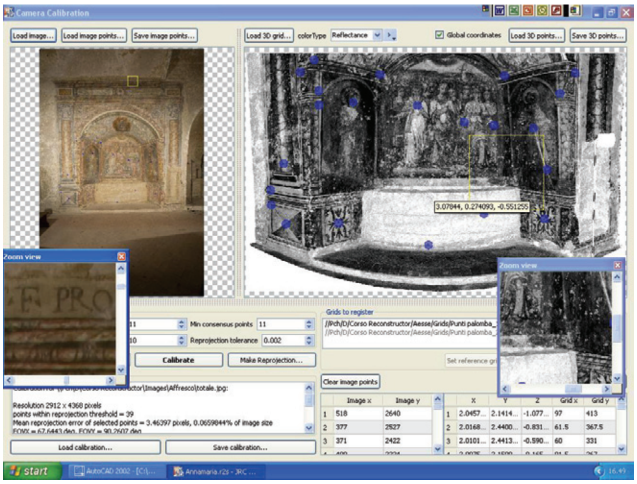

Fig. 12. Survey by 3D *laser scanner*

On the basis of physical phenomena related to the rate of evaporation, and consequently to the crystallization of soluble salts, it was considered appropriate to focus monitoring activities related to the prototype temperature-humidity conditions, inside the building, both in relation to the changing of the external environmental conditions (temperature, humidity, precipitation, orientation to the sun) and at the building characteristics (geometry, materials and construction techniques), also in relation to changes of use (ventilation, heating, presence of people).

It is known that for a correct assessment of the condensation phenomenon, as for freeze-thaw and salt crystallization, it is essential to check the conditions of the internal and external microclimate over time, recording their daily and seasonal variations. It was therefore decided to perform a psychrometric analysis in the area more attractive for the elegance of the finishes and the quality of the structures, most significant in relation to the destinations intended use. The system, therefore, is able to recreate, for each sensor in real time, a psychrometric map, an instrument particularly useful and capable of reproduce graphically the timing of the two main thermo-hygrometric environmental variables: temperature and relative humidity. In this pair of values detected by sensors, the prototype is able, on the basis of a specific algorithm, to associate a third value, that of specific humidity, which is an important parameter to give an account of the actual water content in the environmental air (specific humidity, S.U.).

With this system it is also possible to translate and return the precise measures of the sensors, according to a regular grid of points suitably arranged in the form of thematic maps displayed in *WebGIS* (isochores and isotherms) easy to read and effective for visualizing the distribution of the values in the interior of the rooms under investigation, by combining the individual measurements of temperature and RH% (see Fig.13).

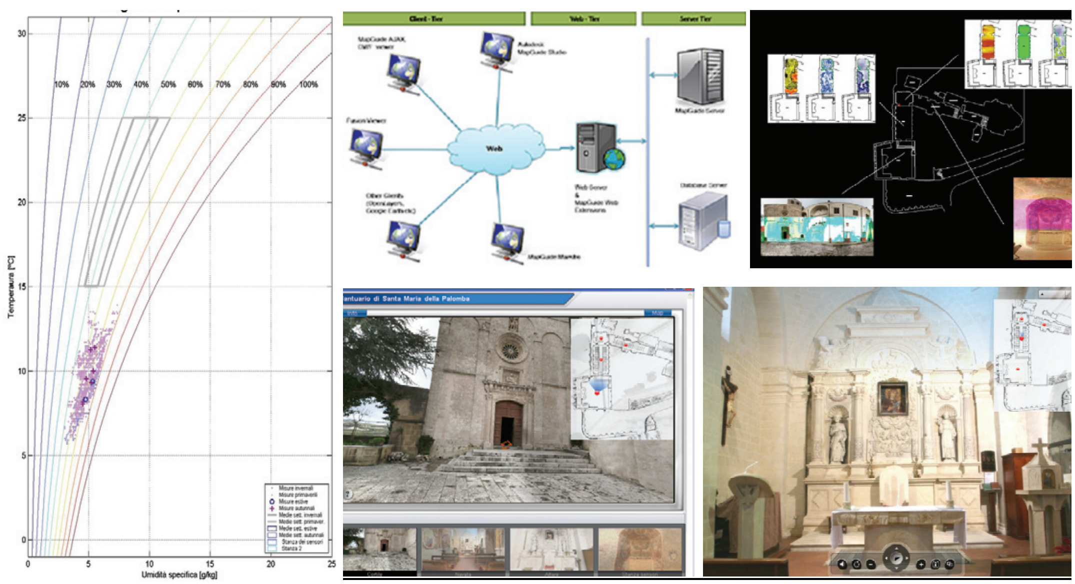

Fig. 13. Symbolic images of the architecture of the remote sensing control, location of areas where there were strongest thermo-hygrometric anomalies and restitution of psychrometric maps through *WebGIS* system

The system allows real-time analysis and consultation of all the measured values of RH%, S.U. and T °C of internal environment to the internal rock construction which, performed with very fast acquisition times of data (in the order of the second), gives comparable measures of the whole area of investigation, under equilibrium conditions.

3. The research results

In a widespread application, the remote reading can be easily repeated in cases of difficult access: if one thinks of the numerous rock-hewn churches in the Mediterranean basin, subjected to remote control [9] [10]. They could be empowered to receive interventions of recovery and restoration, using methods that are supported by scientifically correct information. In terms of energy, in a similar situation with difficult access and lack of electricity, appropriate photovoltaic panels have been used to power the controller that must send data over the *web*, or in alternative situations, by radio

In a strategic viewpoint, the model developed is a *Decision Support System*, designed to simulate the *design alternatives*, where "design" means any decision on asset building, from the analysis of the size and color of the single concave (for example, for the award of a quarry of origin or time of processing), in the planning of maintenance operations, in the broader management of all possible restoration, recovery, restructuring, integration. In this way, it is possible to follow a very interesting both research and business path, perfectly suited to a wide market demand [11] [12].

Moreover, applications arising from the possibility of remote monitoring can reduce the costs of control, and to study the time courses of environmental parameters, both in ambient air, as in the areas to be protected. In this study, an interesting field of application which is to monitor the dewpoint of the frescoed walls has been investigated in terms of control of physical parameters first identified: the displacement of the representative point in the interior of the Mollier psychrometric chart, compared to the condensation curve to the variation of the environmental climatic conditions.

The amendments to the internal thermo-hygrometric parameters, resulting from natural conditions or the climate of areas, involving different reactions on the frescoed walls, can influence the "best practices" for preventing the recovery procedures. Thus avoiding the possibility that it is permanently barred the recovery of these frescoes, if not monitored and if left in a state of neglect.

References

[1] Cotecchia V., Grassi D., *Incidenze geologico ambientali sull'ubicazione e sullo stato di degrado degli insediamenti rupestri medioevali della Puglia e della Basilicata*, Geologia Applicata ed Idrogeologia, vol. XXXII, 1-10, 1997

[2] Grassi D., Grimaldi S., Sabbatini L., Simeone V., Van Der Werf I., *Principali cause del degrado del cospicuo patrimonio artistico ospitato dagli insediamenti rupestri della Puglia*, Giornale di Geologia Applicata 4 73-78, doi: 10.1474/GGA.2006-04.0-09.0137;2006

[3] Fornaro C., Wierdl S., *Sistemi di diagnostica, restauro,manutenzione,conservazione,dei materiali lapidei e degli elementi decorativi*, MURST, Ipogea ;1998

[4] Bartolucci D., *Principi di laser scanning 3D. Hardware – metodologie applicative – esempi*, pp. 100-105, Palermo; 2009.

[5] Campana S., Francovich R. (a cura di), *Laser scanner e GPS. Paesaggi archeologici e tecnologie digitali*, Firenze;2006.

[6] Slob S., Hack R., Turner A. K., *An approach to automate discontinuity measurements of rock faces using laser scanning techniques*, ISRM International Symposium on Rock Engineering for Mountainous Regions – Eurock, Funchal, Portogallo; 2002..

[7] Casadio F., Giangualano I., Piqué F., *Organic materials in wall paintings: the historical and analytical literature*, Reviews in Conservation 6, 63-80, 2004.

[8] El-Hakim S. F., Gonzo L., Girardi S., Voltolini F., Pontin M., *Experience and Challenges in 3D Digital Documentation of Frescoed Walls and Ceilings from Images*, 2nd Canada-Italy Workshop on 3D Digital Imaging and Modeling, Padua; May 2005.

[9] Di Bona, C., Ockham, S., Stone, M. (a cura di), *Open Sources: Voices from the Open Source Revolution*, O'Reilly and Associates, Sebastopol (California), 1999.

[10] Di Corinto A., *Revolution OS II. Software libero, proprietà intellettuale, cultura e politica*, Apogeo, Milano; 2006

[11] Ausserer, K.F., Börner, w., Goriany, M. & Karlhuber-Vöckl, L., *Enter the Past. The E-way into the four Dimensions of*

Cultural Heritage, CAA 2003, Computer Applications and Quantitative Methods in Archaeology. BAR International Series 1227, 16-26,Oxford: Archaeopress; 2004 .

[12] Balis V., Karamitsos S., Kotsis I., Liapakis C., Simpas N., *3D - Laser Scanning: Integration of Point Cloud and CCD Camera Video Data for the Production of High Resolution and Precision RGB Textured Models: Archaeological Monuments Surveying Application in Ancient Ilida*, Proc. of the FIG Working Week, Athens;2004 .

Contributions

Prof. Filiberto Lembo edited the general approach of the research.

Eng. Francesco Paolo R. Marino has structured the methodology, supervised and edited the setting and carrying out the analysis of all non-invasive diagnostic sensing techniques.

Arch. Nicola Ambrosecchia has developed on the 3D survey in WebGIS environment.

La.Te.C. (Building Construction Technology Laboratory) of the University of Basilicata – Potenza, provided the equipment for thermo-hygrometric and thermografic measurements; Logos Innovazione Scrl Society gave instrumentation for 3D surveys.