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Supplementary issue paper

Installation of an environmental monitoring system in the Chapel of Our Lady of Guia, Macau

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Built in the early seventeenth century, the Chapel of Our Lady of Guia is one of the most important heritage sites in the historic centre of Macau. Its architectural features and wall paintings with Chinese and Western characteristics reflect the historical status of Macau as a hub for cultural exchange between China and the West. Since signs of deterioration have been observed on the wall paintings in recent years, it is very urgent and necessary to conserve them. In this paper, we will introduce the modern diagnostic techniques applied in the course of their conservation, including 3D laser scanning, high-definition digital photography, environmental monitoring, thermal infrared imaging, microwave scanning and penetration resistance tests. Comprehensive information on the current state of the wall paintings is collected, providing a solid foundation for their scientific preservation.

Keywords: Chapel of Our Lady of Guia, Conservation, Diagnostic techniques, Environmental monitoring system

Introduction

Built in the early seventeenth century, the Chapel of Our Lady of Guia (Our Lady of the Snow) is one of the most important heritage sites in the historic centre of Macau, which includes more than 20 historic buildings interwoven with adjacent squares and streets, and was inscribed on the UNESCO World Heritage List in 2005. Despite its small size, the Chapel remains a landmark of the region due to its location at the top of Guia Hill. In Macau, both banknotes and coins bear the image of the Chapel of Our Lady of Guia (Fig. 1).

The wall paintings in the Chapel were discovered during a renovation project conducted by the Macao Portuguese government in 1996. All the interior walls and ceiling are decorated with paintings. The themes are mainly biblical characters and stories, decorated with plant and animal patterns painted using Chinese techniques. This combination of Chinese and Western art and culture makes it an unusual work of art in southern China (Dai, 2009) (Fig. 2).

The Chapel has been well preserved over the past three hundred years since it was built. The structure remains intact without any serious damage, though signs of deterioration have been observed on the wall

paintings in recent years. The Cultural Heritage Department of the Cultural Institute of the Macao S.A.R. Government therefore commissioned the Laboratory for Conservation of Heritage Architecture of Tongji University (LCHA) to study, record, monitor and evaluate the environmental conditions and conservation problems of the Chapel, and to devise an improvement plan for conserving the architecture (Dai, 2009).

Many modern diagnostic techniques have been used, both in China and abroad, to study the state of preservation and the causes of deterioration of historic monuments. The LCHA applied some of these techniques to study and record the conservation state of the wall paintings, as well as to identify the causes of deterioration in order to devise a conservation methodology. They included 3D laser scanning to survey accurately the current state of the Chapel and wall paintings (Tang, 2006); high-definition digital photography to record the overall and microscopic views of the paintings; digital sensors to collect the temperature and relative humidity (T and RH) of the paintings and the environment; infrared imaging to study the distribution and extent of moisture in the paintings; microwave scanning to detect changes in moisture content; and penetration resistance testing to study the characteristics of the material of the internal walls.

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Figure 1 Image of the Chapel on the local currency of Macau.



Figure 2 Wall paintings on the north wall of the front hall of the Chapel.

Diagnostic techniques used

3D laser scanning

The 3D laser scanning system is a polar coordinate measurement system where the location of a point is determined by the distance and angle of the point from the pole. It has advantages of speed and high precision, and is widely used in the fields of machinery

manufacture, mould machining, and industrial measurement. Compared with traditional surveying and mapping, 3D laser scanning can record the current state of structures more completely, and the information captured is more comprehensive and precise (Tang, 2006). 3D laser scanning has already been widely used to collect basic information on the

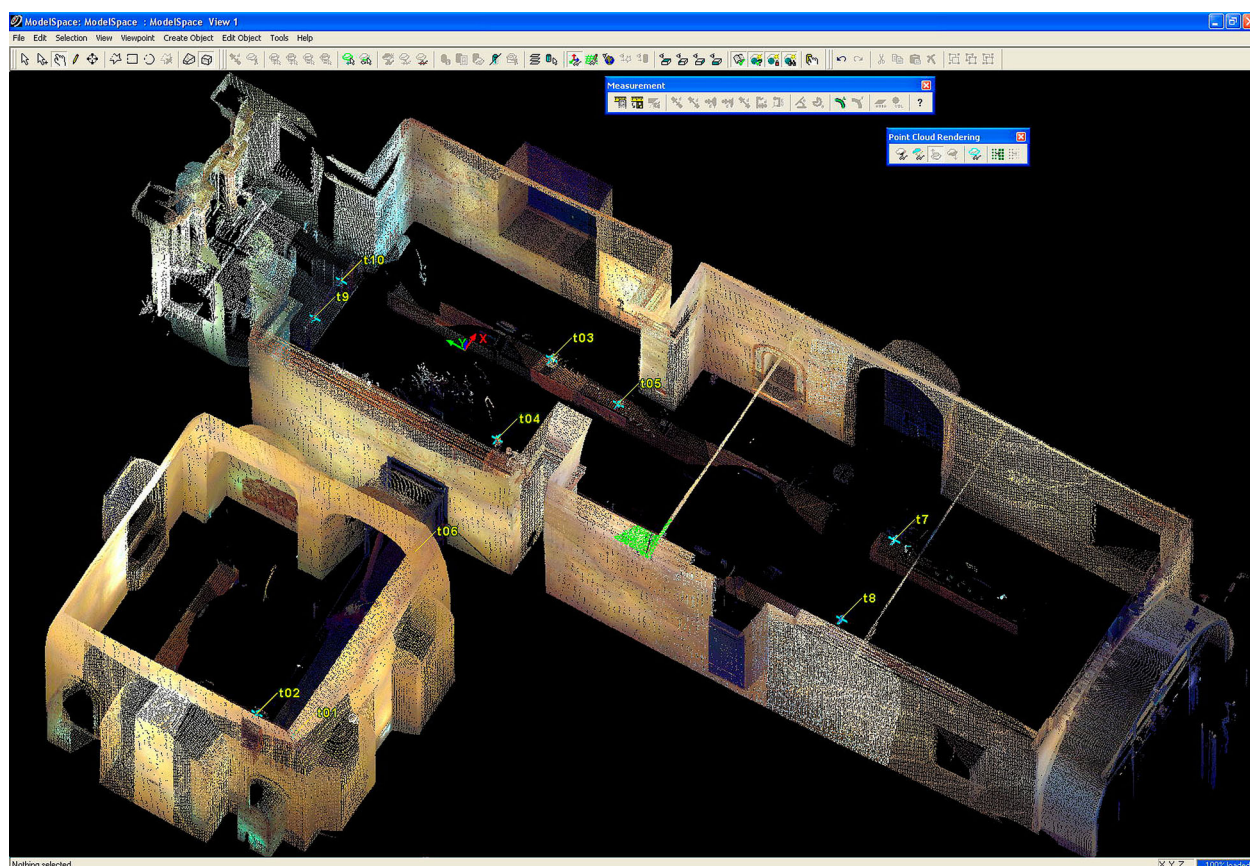


Figure 3 The point cloud of the interior of the Chapel.

fabric at an early stage of historic buildings conservation. Besides essential building surveying and mapping, quantitative documentation of the damage to the wall paintings was carried out in this project, such as the position, size, and shape of damage and losses in order to provide a basic reference for future conservation and maintenance work.

First of all, we used a Leica HDS3000 3D laser scanner to produce a high-precision scan of the whole building including both interior and exterior fabrics, and to collect high-precision (better than 2 mm) spatial information on the building and paintings (Fig. 3). Then we could measure and analyse the position, area, and shape of the damages on the digital images (Fig. 4). Scanning the paintings regularly can help monitor their changes dynamically. By comparing and analysing the point cloud data obtained at different times, we can discover changes to the paintings, especially small changes which cannot be observed easily, such as small-scale flaking. The raw data obtained from regular monitoring should be regarded as an important reference for the proper management of cultural heritage.

High-definition digital photography

High-definition digital photography is a means of collecting information, including the condition, colour, and pattern of the paintings. Special attention has to

be paid to controlling the colour temperature of the illumination to ensure accurate recording of the colours (Tang and Zhang, 2007).

At present, a warm lighting system is used to illuminate the interior of the Chapel to produce an atmosphere appropriate to religious art, which is not suitable for recording the colours of the paintings. It was therefore necessary to use professional lighting equipment with a higher colour temperature (5400 K) (Fig. 5).

Accurate exposure is another important factor to provide accurate colour rendering. The built-in metering system of a digital camera calculates the exposure parameters by measuring the light reflected from the surface of the object, assuming it has a reflectance of 17%. However, as the colour tone of the wall paintings is uneven, the light coloured areas will be underexposed when relying on automatic exposure only. Therefore, an external incident-light meter is required and the camera is set manually.

The interior of the Chapel is not very large, so we needed to use an ultra-wide angle lens. In order to obtain complete coverage of the interior of the Chapel and the wall paintings, we used a Nikon D700 full-frame digital single-lens reflex camera with a 12–24 mm lens. To prevent perspective distortion, a tripod was used to make sure the back of the camera was completely parallel to the objects. A

圣母雪地殿教堂——前殿与拜殿南壁残余壁画现状分析：

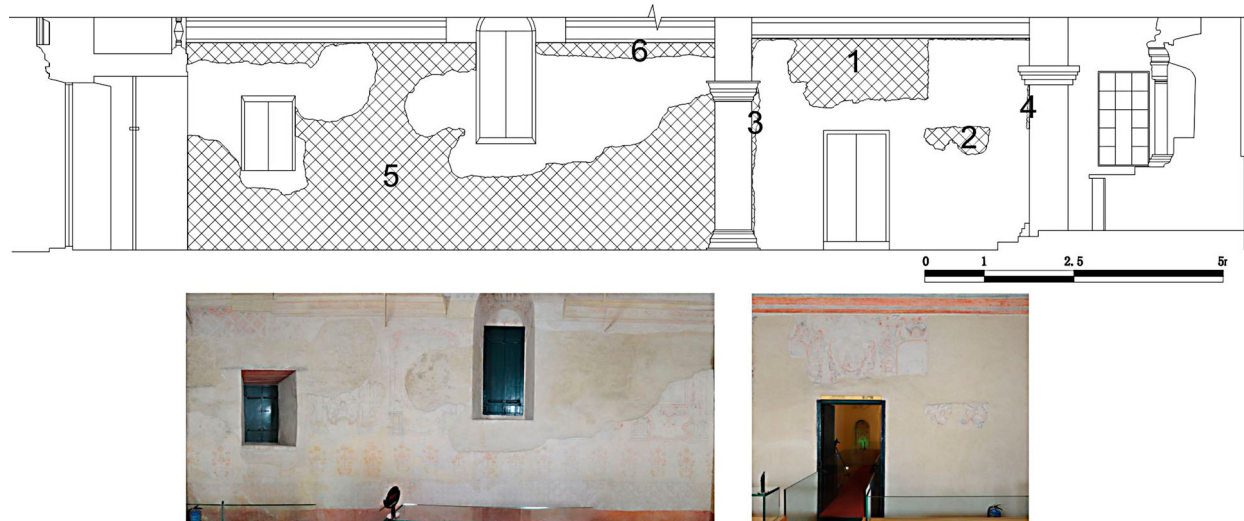


Figure 4 Status analysis of the remaining paintings on the south walls of the front hall and nave. Left: south wall of the front hall. Right: south wall of the nave

Number	Areas of remaining painting	
1	2,310,524mm ²	
2	377,898mm ²	
3	132,274mm ²	
4	25,229mm ²	
Total area of remaining painting on the south wall of the nave		2,945,925mm ²
Original area		14,060,574mm ²
Percentage remaining		20.95%
Number	Areas of the remaining painting	
5	17,535,752mm ²	
6	699,095mm ²	
Total area of remaining painting on the south wall of the front hall		18,234,864mm ²
Original area		27,798,084mm ²
Percentage remaining		65.59%

filming platform almost 2 m high was set up to capture the image of the dome, the ceiling of which is about 6 m from the floor. Restrained by space and distance, we tried to use a Nikon 50 mm standard lens wherever possible, or 105 mm macro lens to take close-ups of the paintings (Fig. 6).

In order to record the condition of the roof, the digital camera was fitted to a drone (Fig. 7). The drone has four power rotors, allowing flying, hovering and rotating. It also has the advantages of steady flying, flexible control, heavy loading capacity, and vertical take-off and landing.

Thermal infrared imaging

The thermal infrared region extends from 2 μm to 1000 μm . Any object above absolute zero will emit thermal infrared rays continuously and its emission spectrum is directly related to the temperature of its surface. The imaging of thermal radiation allows temperature measurement and thermal analysis without contact. It thus serves as an important test method and diagnostic tool for wall painting conservation.

A thermal imaging camera produces a visible real-time image (thermogram) by detecting invisible infrared radiation emitted from objects. A thermal imaging camera is very sensitive; it can detect temperature differences of less than 0.1°C.

From the thermogram, we found that the interior temperature of the Chapel was not uniform and there were large differences in the surface temperature of the paintings above the doors and windows (Fig. 8). This is because the traditional wooden doors and windows are not airtight, ambient air with a higher temperature leaks into the Chapel through the gaps around the doors and windows and affects the surface of the paintings indoors.

The thermogram also showed an uneven temperature distribution in the roof of the Chapel even though there were no doors and windows (Fig. 9). After close examination, we found mildew in the area with lower temperature. This could be the result of roof leakage. The water lowered the temperature of these areas, and caused the growth of mildew on the paintings. Combined with evidence



Figure 5 Different colour temperatures of the lighting caused different colours to be recorded.



Figure 6 Photos of paintings taken by wide-angle lens, standard lens, and macro lens.

from previous aerial photos, it is certain that the leak takes place where the ridges of different sections of the roof join, so it is very urgent to repair the roof.

Microwave scanning for moisture measurements

The wall paintings of the Chapel of Our Lady of Guia are executed in true fresco. Pigment was applied before

the complete setting of the lime plaster so that they would bond together. However, due to the absorption of moisture by the lime, the plaster will change slightly in volume as the surrounding relative humidity changes. The plaster will flake off if subjected to prolonged fluctuation in humidity. It is therefore very important to measure the moisture content of the paintings.



Figure 7 Aerial view taken by four-rotor drone.



Figure 8 Surface temperature difference of wall paintings shown on thermogram.

A handheld microwave hygrometer can measure the moisture content of concretes, bricks, tiles, sandstones, bituminous pavements, timber, synthetic materials, and other building materials quickly and non-destructively (Tang, 2010), up to a maximum depth of 80 cm with calibration. A diagram showing the distribution of the moisture content in the interior and surface of the material can be obtained by using a combination of the handheld microwave hygrometer and multi-

dimensional moisture distribution imaging software (Fig. 10).

By measuring the moisture content at different depths in the walls of the Chapel, it was concluded that the existing coating on the wall had already lost its waterproofing ability and that water can penetrate into the walls; because of the thickness of the walls, the rainwater affected the interior less. Rainwater was the source of moisture in the exterior walls, and

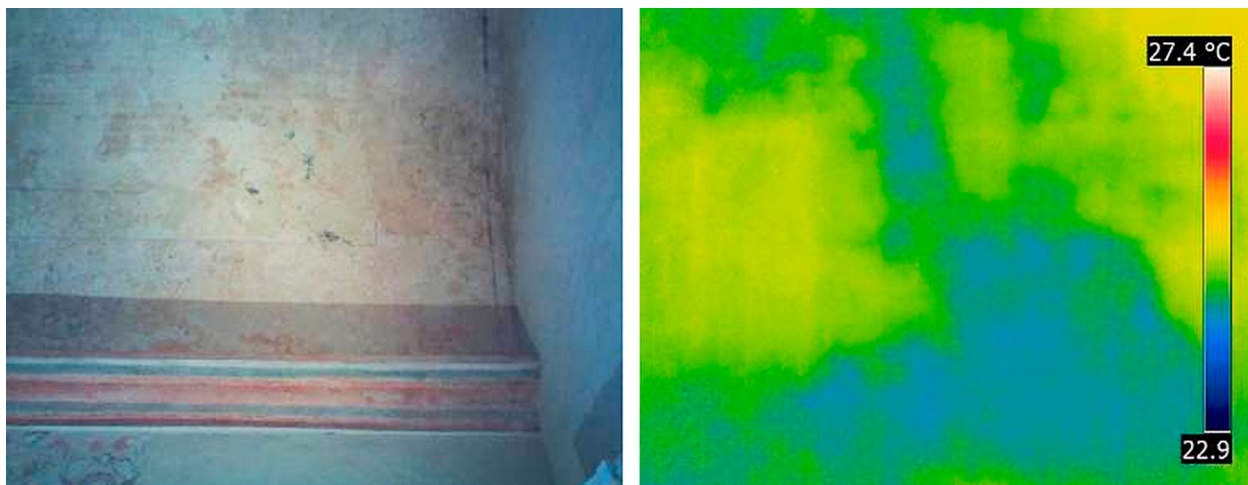


Figure 9 The thermogram shows that the temperature of the area affected by mildew was lower.

the moisture at the bottom of the walls was caused by rainwater and splashing. The high moisture content on the surface of the ground layer may be due to water condensation after switching off the air conditioner during the night.

Penetration resistance tests

The walls of the Chapel of Our Lady of Guia are almost 1 m thick, and their internal composition will influence the surface of the paintings, especially the strength of the material close to the surface. Therefore, it is necessary to understand the internal composition and strength of the walls quantitatively. Penetration resistance testing is a micro-invasive method used to measure the thickness and strength of the surface layers of walls. A 3 mm drill bit was used to drill a hole in an unpainted area of the wall.

The penetration resistance apparatus can measure the drilling resistance continuously and display the results immediately, and absolute values of strength can be obtained after calibration (Fig. 11).

The results indicated that the strength increased sharply after drilling to a depth of 10–20 mm. With microscopic examination and identification of the composition of salts in the materials, we confirmed that the original ground had two or three layers, and that the total thickness was between 10 and 20 mm. The bottom layer was light yellow lime plaster with clay added, and the wall face was white and almost pure lime (lime mortar mixed with paper strips or straw). There were residues of straw in the two layers, so they were probably traditional Chinese rice straw lime mortar. The strength analysis showed that the interior was high-strength stone masonry.

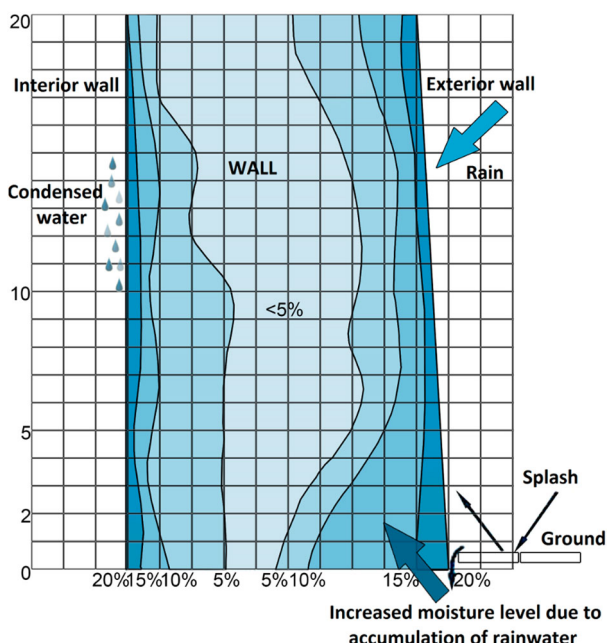


Figure 10 Humidity distribution in the interior and on the surface of the wall of the Chapel with cause analysis.

Environmental monitoring

The lime plaster will expand when the temperature increases, and shrink when it decreases. This would cause the surface layer to lift and peel. When the



Figure 11 Penetration resistance testing the interior and surface of the wall of the Chapel.

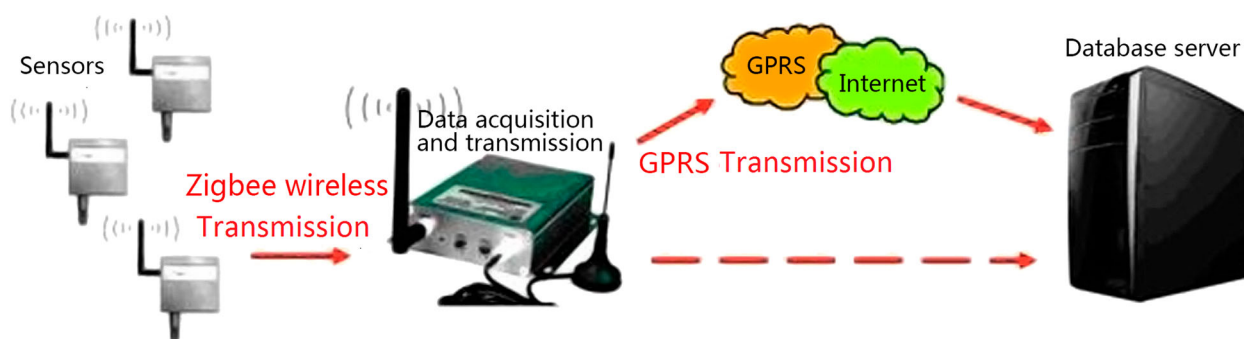


Figure 12 Schematic diagram of collecting and transmitting environmental data.

temperature drops from 40°C to 20°C, the lime will shrink by 0.11 mm/m. Controlling the variation in surface temperature of the paintings within a narrow range is an important measure for their conservation. Meanwhile, the lime plaster will expand when the relative humidity increases and shrink when it decreases, causing lifting and peeling of the surface layer. The paintings will also be damaged by air pollutants in the presence of water on the wall surface, in particular by condensation. Therefore the paramount task is to control the ambient temperature and relative humidity both inside and outside the Chapel to prevent condensation. To this end, an environmental monitoring system is required to collect, store, and analyse the temperature and relative humidity data.

The collection of environmental data used unattended real-time online monitoring and wireless transmission technology. A remote database was established on the recipient side and the user can log in and access the database with authorization (Fig. 12).

The advantage of the wireless monitoring system is the flexibility in installing the sensors. Distant users can check the real-time monitoring data online and the operation status of the equipment. The data can be downloaded, processed and analysed at any time, and the software has many abilities for processing and interpreting the data, so it is convenient to retrieve and manage the data. The system reserves many functional interfaces for further expansion, system integration and reverse control of the air conditioning system. With a large capacity for data storage and inquiry functions, the database can provide comprehensive and reliable data services. The processing speed of the database is fast. It is easy to use, with wide scalability, good portability, and high reliability. The system can also be developed in a sustainable manner. After storing, collating, searching, and analysing the monitoring data, the software we have developed can help users to identify the potential risks. The software has the functions of real-time display, statistical analysis, data retrieval, alert function, user-defined data computational formulae, and grouping management for different users.

Based on the spatial composition and the positions of the wall paintings in the Chapel, the temperature (T) and relative humidity (RH) monitoring system consisted of 32 sensors in six groups in different locations. Three groups of sensors were installed in the long narrow corridor and the front hall; one group in the chancel; one group in the sacristy where a relay device was added to transmit signals from the far end of the building, and one group was installed outside the Chapel. Each group had more than one sensor to record the data (Tang, 2010).

As it was not convenient to collect data on-site regularly, the system was designed for unattended automatic remote monitoring. The operation status of the sensors and the data collected were transmitted through a wireless network and stored on a main computer for regular data transmission through a mobile communication 3G network to an internet server. A Dell OptiPlex 760 computer (specifications: Intel E5300/2.6 GHz, Intel Q43 Express mainboard, 2G RAM DDR2800, Samsung SSD 840 EVO 120 GB solid state hard disk) was used for data collection, storage, and transmission. The cooling and safety protection of this host computer were enhanced.

It was necessary to consider the special requirements of a heritage building when selecting the hardware for monitoring: small size, high stability, and low power consumption were the criteria for consideration. Since the Chapel was not suitable for installation of the large T and RH sensors currently available on the market, the LCHA developed wireless sensors for the project. The sensors were made from the SHT series digital T and RH data collection chip with a Zigbee wireless transmission module. The SHT sensor utilized patented CMOSens technology to integrate a thermo-humidistat comprising a single-capacitor humidity sensor, a bandgap temperature sensor, a 14-bit A/D converter, and a two-wire digital connector. These sensors were small, had low power consumption, were fast in response, simple to connect and had high interference resistance, thus meeting the requirements of reliability and long-term stability for monitoring.

As the spatial arrangement of the interior of the Chapel is very simple, the sensors were placed in such a way to minimize their visibility. Original decorative lines and existing steel reinforcing bars were used to install and secure them. The main computer was placed in the position of the original choir stall in the hall above the entrance of the Chapel, which was not open to the public. A separate entrance to this area facilitated maintenance.

The monitoring system has undergone fine-tuning and test-running since the hardware was installed. T and RH data were collected every 10 minutes by the 32 sensors. From April to October 2013, nearly a million pieces of data were collected. This indicated that the interior temperature of the Chapel ranged from 15.1°C to 29.3°C while the RH ranged from 67% to 100%. Detailed analytical studies will be carried out by building environment specialists after the monitoring system has been in operation for a sufficient period of time.

Results and discussion

Preliminary studies indicated that the murals were painted onto a lime ground while it was still wet. The present flaking and detachment of the paint layer from the lime ground may have been caused by the expansion and contraction of the lime ground with fluctuations in temperature and relative humidity. Apart from seasonal and diurnal changes, changes in temperature and relative humidity inside the Chapel were complicated, with wide fluctuations. The operation of the air conditioning and the presence of visitors affected the indoor environment. In addition, the temperature and moisture content were different in different positions and at different depths in the walls.

The weather in Hong Kong, Macao and Southeast Asia is relatively high in T and RH, and air conditioners are widely used in urban areas. The rapid

alternating cycles of cooling/heating and dehumidifying/humidifying have a great impact on building fabric. The T and RH monitoring system installed in the Chapel will be used for long-term environmental monitoring inside and outside the Chapel and for studying the effect of environmental changes on heritage buildings. It can also be used as a reference for the conservation of similar built heritage.

Concluding remarks

It has been two years since we started the conservation of the Chapel of Our Lady of Guia. The Cultural Affairs Bureau of the Macao S.A.R. Government has attached great importance to this project and given ample support and understanding for the fundamental research at this early stage. Scientific study and research were fully conducted before carrying out the specific conservation measures. We thus had the opportunity to apply many modern specialist techniques to collect and analyse information on the current state of this historic building, which provided a solid foundation for preserving it in a scientific and ethical manner.

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