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Development of reversible intelligent prosthesis for the conservation of sculptures. A case study

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Abstract

The application of preventive conservation measures after restoration processes is a sustainable method to control and mitigate possible deterioration and damage to Cultural Heritage. Preservation requires monitoring physical parameters that influence the monument. This document presents the development of a versatile hybrid system based on a 3D printed prosthesis implanted with sensors to collect relevant environmental data. This novel system has been applied to a work of relevance, the Stone Sepulcher of Queen Mary of Castile, located in the Royal Monastery of the Holy Trinity of Valencia (Spain). The development of such an intelligent prosthesis aims to improve the conservation of a work of art. The system presented here is completely reversible, leaving any trace on the sculpture where it was inserted after removal. This intelligent prosthesis can monitor the environmental conditions and send them to a remote server in the cloud. The results have demonstrated the viability and suitability of the procedure and present an innovative solution applicable to other pieces of Cultural Heritage.

Keywords Intelligent prosthesis, IoT, advanced Cultural Heritage monitoring, 3D virtual model, 3D print, Sepulcher of the Queen Mary, Monastery of the Holy Trinity (Valencia, Spain).

1. Introduction

Preventive conservation is a method of work that helps establish and control the deterioration of Cultural Heritage. After the restoration processes, it is necessary to establish management plans that provide sustainable action models. The monitoring of environmental measures, indoors and outdoors, turns out to be very useful to preserve the work of art in the short and long term [1-3]. The development of new methods to control climate parameters helps to implement actions and preserve monuments [4-9]. All of these, linked to the use of new digital technologies, become tools with great potential and essential in the intervention and preservation processes [10-14].

In the last decade, 3D technologies have experienced a strong and rapid growth that have led to the appearance in the market of a multitude of highly sophisticated materials and instruments with a multitude of technical possibilities (3D printer, 3D scanner, AR glasses, among others) [15-20]. This has led to a greater transfer and knowledge of heritage to a broader audience through 3D models in its most diverse virtual platforms [21]. In addition, 3D printing technologies allow the creation of tangible reproductions of these very useful and versatile 3D digital models during the processes of intervention in Cultural Heritage [22].

This fervent technological explosion involves, in the field of conservation and restoration, a new axiom and a change in the praxis of interventions. Volumetric reconstruction using copies/prostheses is one of the phases that generates the most controversy among different heritage professionals due to its influence on aesthetic reading and the ethics of the procedure [23]. There are various possibilities in the realization of reintegration, replacements and/or copies, conventional and/or digital [24-28]. Nevertheless, they all have a point in common: the treatment must be totally reversible [29-31]. According to the conventional procedure, obtaining prostheses involves frequent contact with the original that could entail certain risks of deterioration. The present investigation is the result of a search for innovative solutions in the restorative process and maintenance of works with volume losses. The purpose is to reconstruct the morphology without acting directly on the work through the use of digital manufacturing tools to subsequently incorporate a series of detectors that control environmental conditions in a timely manner.

In previous works, we showed the possibility of registering in real time sculptures and ornamental elements; developing the post-processing of data and obtaining 3d models with very high resolution and finally printing the objects. Thus, a systematic method was developed, at the same time that direct contact was avoided and reversibility was guaranteed [32-34]. In these previous works, real works of art were used in which the viability of the developed method was studied. This work shows the potential of this approach by adding new advances and using them on an emblematic work destroyed at certain moments in its history: the Stone Sepulcher of Queen Mary of Castile, located in the Royal Monastery of the Holy Trinity of Valencia (Spain).

2. Research aim

This study has been applied to an emblematic real case, the Stone Sepulchre of the Queen Mary of Castile (María de Castilla)(S. XV), located in the Royal Monastery of the Holy Trinity (Santísima Trinidad), in Valencia (Spain). Queen Mary of Castile (Segovia, 1401- Valencia, 1458) was the wife of Alfonso V El Magnánimo, king of Aragón (Medina del Campo, 1396 - Naples, June 27, 1458). The predilection that Queen Mary maintained for the Clarissian nuns and her periods of spiritual recollection in Valencia responds to her being buried in a splendid Gothic sepulcher in the monastery itself [35]. It is the only royal tomb located in the Valencian Community. Its construction in calcarenite stone is attributed to the great master builder Antoni Dalmau (active in Valencia from 1440 to 1453) [36].

The sepulcher, located in an outstanding angle of the cloister, has an ornate ogee arch and topped with fine plant motifs, flanked by two pinnacles and a niche of ashlar masonry. In the lower part, in front, it contains three crowned shields and enclosed in tondos: the arms of Aragon, Sicily and Castile [37]. At present, these sculptural details are mutilated for various reasons, the Napoleonic invasion (1812) and the overflow of the Turia River (1957), among others (Fig. 1). The set was declared a National Historic-Artistic Monument in 1982 and a *Bien de Interés Cultural* in 1983 ("good of cultural interest"; a category in the Spanish heritage register).

In 2017 the restoration process was undertaken, which consisted of a thorough cleaning of the surface dirt, remains of mortars and pigeons from birds that nested in the monument. Finally, the innovative system of monitoring the tomb was proposed through the development of intelligent prostheses.

Fig. 1 (a-c). The Stone Sepulcher of the Queen Mary of Castile", Royal Monastery of the Holy Trinity (Valencia, Spain). a) General view of the Sepulcher; b) Zones of the tondos where it observes the coats of arms damaged; c) Detail areas of the missing sections of tondo where the study is applied.

3. Materials and methodology

For the study of the tomb and development of the intelligent prosthesis, several non-destructive imaging techniques were used: digital photography, photogrammetry and laser scanner as well as various data processing software and 3D digital modelling.

In the 3D record, a portable scanner with structured white light Go!Scan50 was used, with a resolution of 0.5 mm - 2 mm and with a camera for chromatic registration (Creaform). In the data processing, a graphics station MSI WS72, Intel Core i7-6700HQ, 16GB RAM, Nvidia Quadro M2000m was used. An SLA Form2 stereolithographic printer (Formlabs) with a resolution range of 25-100 µm of layer thickness, UV laser of 250 mW and 140 µm for printing the prosthesis was used. NdFeB magnets were selected with a Ni / Cu / Ni coating with magnetization in the axial direction (Supermagnete) and acrylic resin Paraloid B72 (50% w/v in acetone) (Rohm and Haas) to join the prosthesis with magnetic systems to the surface of the tomb [38-39]. VXelements (Creaform), Zbrush (Pixologic) and Preform (FormLabs) software were used for data processing, processing, 3D modeling and prosthesis printing, respectively. Ambient monitoring was performed using the Bosch BME680 sensor [40] measuring ambient temperature, barometric pressure, relative humidity, and Volatile Organic Compounds (that enable to measure the air quality of the environment). Mechanical monitoring was performed by the MPU-6050, a 6-DOF IMU (six degrees of freedom inertial measurement unit). The chip combines a 3-axis accelerometer with a 3-axis gyroscope.

The methodology carried out was structured in four phases. a) the acquisition of data obtained from a GO!SCAN50 laser scanner with VXelements (Creaform) software and post-processing of data, obtaining a 3D virtual model at very high resolution; b) digital modelling, printout and painting of the prosthesis, c) installation of thermo-hygrometric control sensors and, d) verification of the system.

In the first place, the data collection was proposed in order to obtain an optimal visualization of the grave and thus facilitate the subsequent digital processing of the modelling of the missing areas. For this, the scale of the work, the number of registration sessions, the scanning parameters and the resolution were taken into account. The data were obtained through successive sweeps of structured light on the surface and on the different sculptural-ornamental elements and missing areas with a resolution between 0.6 and 2 mm to be subsequently merged. The post-processing consisted in the elimination of unnecessary data (noise, isolated parcels) and fixing mesh errors (inverted polygons, narrow bridges, or small missing). Finally, an alignment and fusion of the different sessions was carried out and the chromatic information was imported. Fig. 2 illustrates the final mesh obtained by the software.

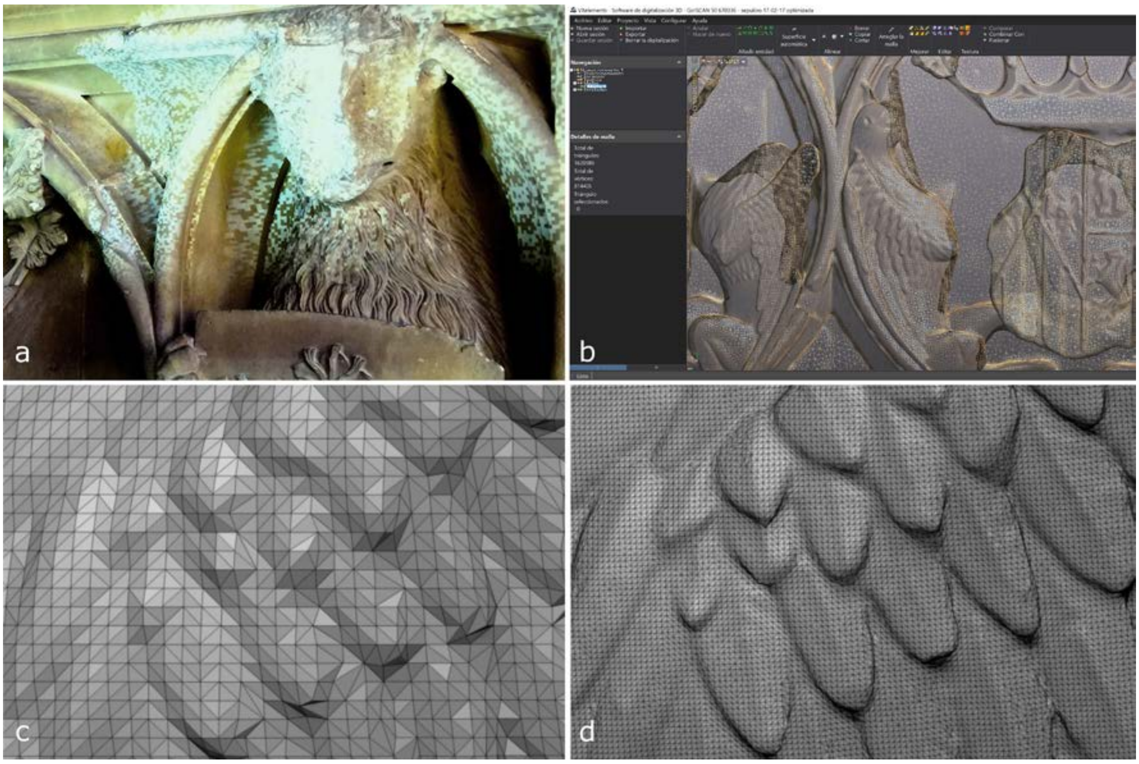

Fig. 2 (a-d). Phase of 3D registration and post-processing. a) Detail of the structured scanner light projected on the surface of the work. b) Screenshot showing the VXelements registration software (Creaform) with the mesh obtained at 2 mm resolution. c-d) Detail of the mesh obtained at 2 mm resolution (left) and the mesh obtained at 0.6 mm (right).

Secondly, the reconstruction of the volume was carried out by means of digital modelling from the data exported to the Zbrush modelling software (Pixologic). For this phase, on the one hand, all existing information about the coats of arms and Gothic heraldry was collected and, on the other hand, the parts of the griffins adjacent to the coats of arms present in the tondos of the tomb were taken as reference. Through the selection of present parts, and the use of the ‘mirror tool’ and the ‘fusion of fragments’ of the missing ones were digitally reconstructed. From a general volume, the fracture zone was adjusted with the use of booleans [41], reaching the continuity of the detail of the texture and, thus, giving the prosthesis a greater homogeneity (Fig. 3c). The sculptural detail was accentuated to avoid any loss during the 3D printing process and corresponding post-curation. Likewise, the internal elements designed to house the magnetic system for securing the prosthesis according to the theoretical method [39] were designed. The last step of the digital volume treatment consisted in the creation of the shell (shell) of the piece. A thickness of 1.2 mm was chosen which gave the piece lightness, poor contact, optimum resistance, good level of detail and sufficient space for the inclusion of the sensors.

Then, the prosthesis was obtained using a 3D stereolithographic printer (SLA) Form2 (Formlabs) using a photopolymerization resin. This printer was chosen because the resulting parts exhibit a higher level of detail and a lower deformation tolerance with respect to other additive manufacturing technologies (e.g. Fused Deposition Modeling, FDM). Thus, the resolution of models with SLA technology is determined by the optical point of the laser that applies light for polymerization, whereas the FDM technology, the resolution is related to the size of the extrusion nozzle and the precision of the extruder's movements. The prosthesis has approximate dimensions of 20 x 20 x 5 cm (height, width, depth). To do this, the optimized file was imported into the Preform software of the Form2 printer and, the print was adjusted to 0.1 mm layer thickness, resulting in a total of 1,656 layers, and printing time of 11 hours and 15 minutes. Finally, the resin excesses were eliminated in an isopropyl alcohol bath, and the post-curing was carried out by means of a UV treatment (1 h), at 450 nm of wavelength, achieving the optimum physical-mechanical conditions. Subsequently, the surface of the piece was treated chromatically to below tone with Acrylic Studio colours of Vallejo (Fig. 5d).

Third, the 3D printed prosthesis in this project does contain a monitoring system built around a dual-core Wi-Fi-enabled SoC (system on a chip) that is both the brain and the data communications system to gather environmental information and to forward it wirelessly to a server on the Internet. All the required components, including the batteries that power the system, are hosted inside the prosthesis, which has been modelled to have an internal cavity with the proper shape to hold them inside. Thus, the prosthesis experiences the same environmental conditions as the rest of the sculpture. The monitoring system measures ambient air parameters: temperature, relative humidity, barometric pressure, and air quality. But it could also measure mechanical parameters such as acceleration by a three-axis accelerometer to register any type of motion it might experience, due to seismic, transportation, or vandalism events. The ESP-32 module by Espressif Systems [42] is a good compromise between all these requirements while still being capable of handling all the software needs. This is not only a processor but a complete system that includes a dual-core 32-bit processor including Wi-Fi (802.11n) and Bluetooth wireless interfaces. A group of independent developers also made available a set of libraries to use it with the Arduino IDE, which opens up a sizable number of libraries for many types of sensors.

Lastly, the verification process worked as follows: the intelligent prosthesis circuit was tested for correct functioning before it was inserted into the prosthesis. Next, the intelligent prosthesis was tested to work and transmit properly in the lab and later in the vicinity of the sepulcher. Finally, the intelligent prosthesis was installed on site, using the magnetic system.

4. Reversible intelligent prosthesis

In this section, the materials and methods used to build our system will be shown. The development of the hybrid system consisting of a 3D printed prosthesis and a series of physical sensors was thought to actively improve the conservation of the work of art exposed to the elements. The proposed system combines two important features for preventive conservation: It is completely reversible (it can be removed without leaving any trace on the sculpture) and, at the same time it can monitor environmental conditions and send them to a control system (cloud).

The computer system of the prosthesis required a set of conditions that were taken into account in the overall system design: a) Small footprint and low power consumption; b) Wireless communication capability and, c) Good commercial availability.

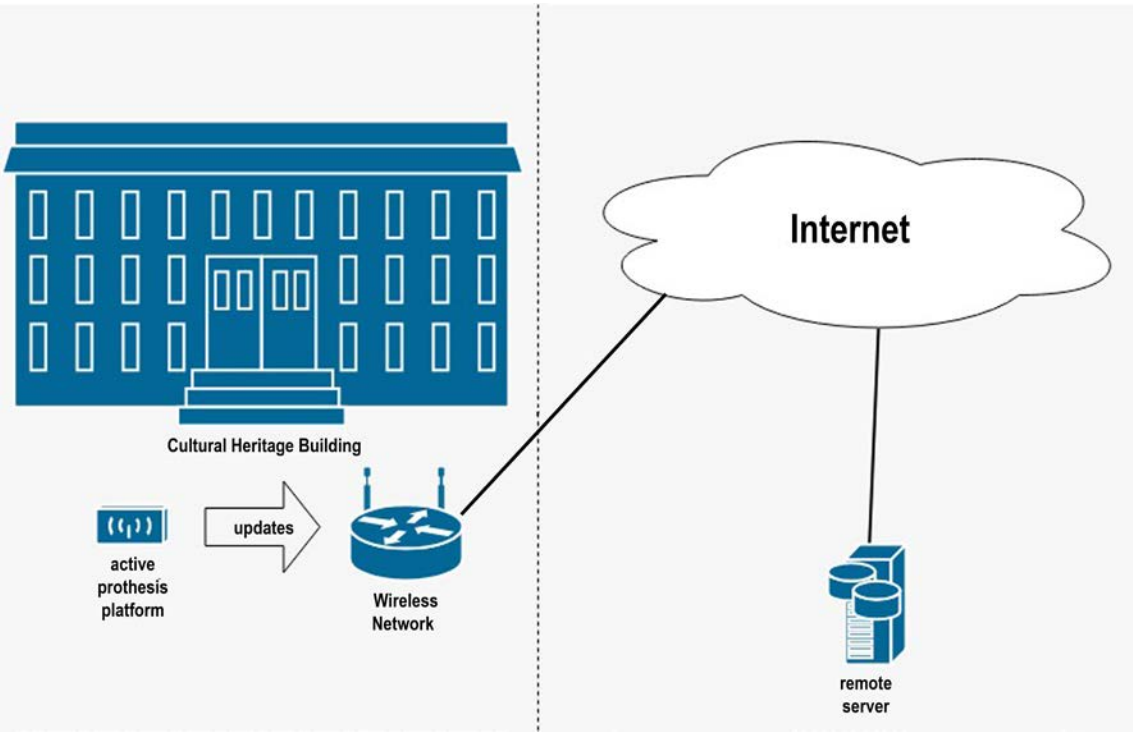

Fig. 3. Active prosthesis uses the building's existing Wi-Fi network to send updates from sensor data to a remote server over the Internet.

In the project presented in this paper, ambient monitoring and data transmission happen every minute of the day. The prosthesis relies on the building’s Wi-Fi network coverage to get access to the Internet as shown in Fig. 3.

As shown in Fig. 4a, the intelligent prosthesis will wake up each minute to gather new data from the sensors and it will connect to the Wi-Fi network and it will send the latest recorded sensor data to an Internet server. This way it can be remotely monitored and gathered data is safely stored. In its simplest configuration, the intelligent prosthesis may consist of only three basic elements as outlined in Figure 4-b: the ambient sensor, the main controller in the form of a complete system in a single chip and a battery to power it for a long period of time. For the temperature, humidity and pressure sensor the BME680 chip by Bosch was selected for a number of reasons: it is really small, 3x3x1 mm and aimed at low-power applications and long term stability. It offers a good level of accuracy of +/- 0.12hPa, +/-0.5ºC and +/-2.5%RH within the 0 to 65ºC temperature range. The sensor is also capable of measuring the presence of volatile organic compounds (VOC) from paints, lacquers, cleaning supplies, adhesives or alcohol, that can be used to estimate the air quality. BME680 is a completely digital sensor, which means all the accuracy of the measurements depends on the sensor itself and not on the processor it is attached to, which ensures the quality of the measurements is not going to be compromised by the selected processor in charge of processing, storing and transmitting the different magnitudes measured by the sensor. Depending on the case, the battery may be recharged using local resources (i.e. energy harvesting [43]) or just replaced by a fresh one when needed. In this particular case, we opted for the latter so a battery replacement will be scheduled when it is running low.

Having all data transmitted and stored in the cloud allows us to create new applications on the server without the need of making changes on the sensor’s software. One example of such a capability is the addition of a “limits-reached” report on the server to notify the person responsible about any measured variable that has exceeded the normal values (i.e. temperature too low).

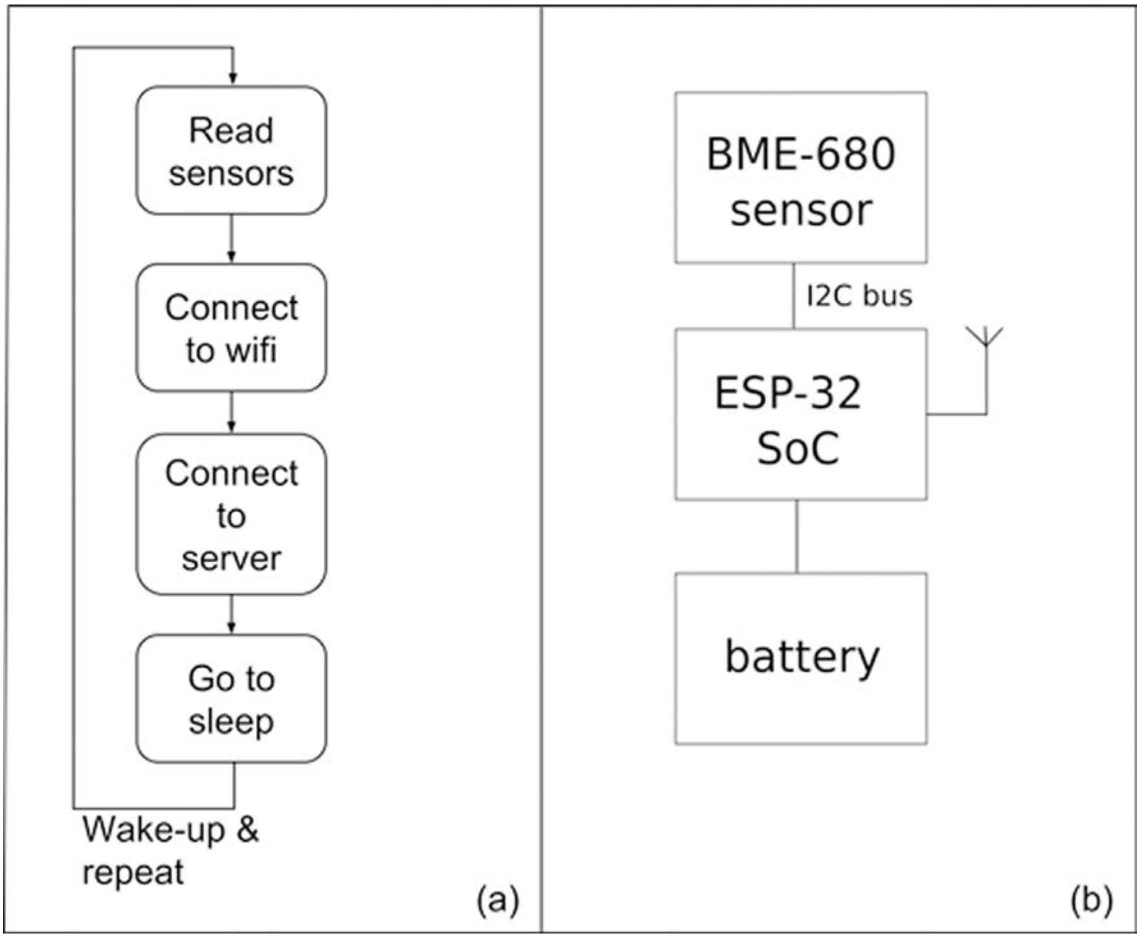

Fig. 4. a) This is the endless loop in the intelligent prosthesis software. b) These are the main components of the intelligent prosthesis, with the ESP-32 System-on-a-Chip with wireless capabilities as its core.

The system uses the MQTT protocol [44] to send the gathered data contents to the free IoT (Internet of Things) server (located in Ausburn, VA) of Adafruit company. Using that service avoided us the need and cost of setting up our own server platform. However, as the number of the prosthesis to be monitored grows, the limits of the free plan are quickly reached and then a monthly fee is due. Using a commercial service allowed us to focus on the prosthesis development. But for a sizable number of nodes, it makes sense to create a dedicated server infrastructure.

Finally, the prosthesis with the sensors adhered with magnetic systems in the area of the tomb. Taking as reference the theoretical model developed by Rodríguez, et al. [38-39] and, having the prosthesis as a whole weighing approximately 130 g, the magnetic force required was 1.27N. For this, four pairs of magnets model S-02-02-N (Supermagnete) were used, each of which provided a force of 1.47 N, according to the manufacturer's specifications, and placed in opposite magnetic configurations to reduce the magnetic field thus closing the magnetic flux.

5. Results and discussion

When restoring a work of art that is outdoors, it is of particular interest to have a system for controlling the surrounding environmental conditions. The monitoring in the previous processes, during and after the treatments, are indispensable to this day. This planning during the works carried out in the Stone Sepulcher of Queen Mary of Castile shows an interest in conserving, documenting, maintaining and disseminating the Cultural Heritage.

The research carried out on the tomb has made it possible to record it completely in 3D so that it can be visualized in web platforms of virtual musealization and interact with the digital model through a viewer based on WebGL technology. This has allowed a greater transfer and dissemination of this heritage among a wide audience of researchers and academics.

On the other hand, the digital model has allowed to complete the missing volume of the parts of the tondos so that the magnitude and genius of the detail of the carving made by the sculptor can be contemplated (Fig. 5a). Ethics and aesthetics have combined to recover the essence of the work of art without prejudice to it (Fig. 5b and 5c). This work highlights the use of other technologies and digital tools (virtual and augmented reality) that will improve the analysis of the visit to the monument.

Fig. 5 (a-d). 3D reconstruction of the Griffins. a) Digital model of the missing areas of the tondos. b) Detail of the area of a tondo without volume. c) Detail of the digitally modelled area. d) Prosthesis printed with SLA and treated chromatically.

The use of the technique of additive manufacturing by SLA has achieved a high level of detail and a finish of the prosthesis according to the surface texture of the original. Of the six Griffins that were missing, one was chosen and finally printed in 3D to house the environmental sensors. It should be noted that it has been decided to keep the prosthesis partially open on its sides to facilitate the exposure and data collection of the sensors. The chromatic treatment has maintained the chromatic discernibility of the prosthesis at close range being imperceptible at a long distance (Fig. 5d). The magnetic systems adhered both in the horizontal and vertical fracture zone have correctly attached the prosthesis and the rest of the environmental sensors respecting the reading of the piece (Fig. 6). According to theoretical model [38], magnets placed in opposite magnetic configurations reduce the magnetic field thus closing the magnetic flux.

Fig. 6 (a-d). Phase of installation of the prosthesis in the area of missing tondo of Arms of Castile. a) Volume missing zone (line) where the magnetic system is observed (arrow) was used to adhere the prosthesis. b) Internal part of the prosthesis in which the environmental sensor system is located and the tabs with the magnetic systems (arrows). c) Placement of the intelligent prosthesis. d) View of the area of the tondos with the intelligent prosthesis in operation.

As the Fig. 6b shows, the battery, processor board and sensor board can fit neatly in the inside of the prosthesis and with one update per minute, the power consumption is below 0.15 milliamperes while the system is sleeping and the average energy consumption is 18 mAh per hour, that includes the Wi-Fi reporting every minute. This means a 3000 mAh battery can last for a week. By reducing the report rate to one sample per hour instead of one per minute, the same battery will last for a year.

Please note the system can measure battery voltage and report it as one additional variable, which allows remote monitoring of the battery status too. So battery replacement can be scheduled in a way the sensor operation is never interrupted by a lack of power.

The proposed system relies on the availability of a Wi-Fi network on-site and that our system is granted access so it can use the local wireless network for its reporting functions. If such infrastructure were not available, a cell phone could be used to provide the necessary wireless Internet access to our system.

Given that the operation of the electronics is not continuous but it is only on for a short period of time, there is virtually no heat generated by the electronics that could otherwise distort the temperature measurements by the sensor. This, together with the fact that the prosthesis does not create an air-tight fit allows us to keep the sensor completely inside of the resin shell and still get good measurements of the exterior conditions (a comparison was made with another sensor outside of the shell to find no relevant difference).

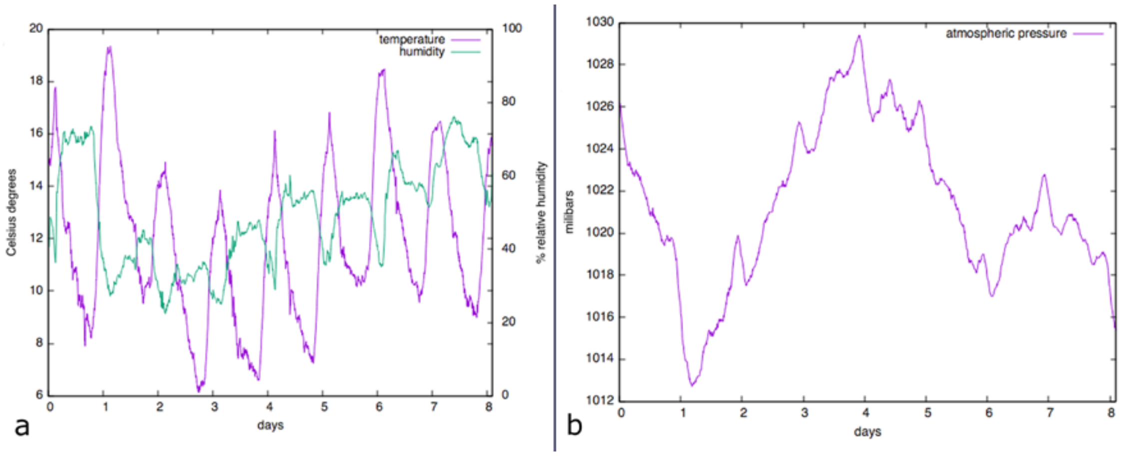

Fig. 7 (a-b). Measured data. a) This graph shows temperature and humidity values. b) This graph shows the evolution of the atmospheric pressure over the same period.

The result of eight days of measured data is shown in Fig. 7, where the temperature and humidity evolution change clearly every day, warming up in the morning to get colder at night and, it can be observed that when temperature raises humidity drops, which makes sense. In addition, these results also prove that the system works properly. On the other hand, pressure change evolves more or less independently of daylight. Based on the recorded data, a set of triggers could be set to signal potentially dangerous conditions to be reported by email to a person responsible.

6. Conclusions

This development of the application of a reversible intelligent prosthesis on a real work shows the null contact without risk of deterioration, the partial recovery of the volumetric reading and the monitoring of environmental conditions in the field of conservation and restoration of sculptural and ornamental works. The methodology developed in this work will help the restorer to consider volumetric reconstruction through the use of current digital technologies and to control the environmental parameters that surround the work effectively. There are few examples in which the use of thermo-hygrometric sensors are presented in an affordable way without being limited by the skills of the conservator/restorer. This intelligent prosthesis system, unlike other commercial sensor platforms, is open-source hardware than can be tailored to the needs of each work or Art (ie: detection of temperature limits, humidity, CO2 levels, bird deterrents, GPS, etc). Trigger conditions can be set to cause warning messages to be sent in case of anomalies, not only of the environment of the work but also to the work itself (for example, unexpected acceleration). The key point of our development is not only that the intelligent prosthesis can be inserted with the restored work of art but the fact that our solution creates a connected monitor that is sensing the environment in which the artifact is placed. We have made every effort to create a system that is easy to replicate and we have made the software available, so other members of our community can use it. Additionally, it is the first work where the sensors are inserted inside a 3D printed prosthesis and, the whole, is attached to the original with magnetic systems. This approach guarantees the minimum incidence of the prosthesis on the surface of the original work, involves a discernible action and, a sustainable maintenance. The hybrid system has shown its viability and reversibility after the intervention without interfering with readability, improving its conservation and diffusion.

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