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Photonics for the virtualization of cultural heritage

Fotónica aplicada a la virtualización del patrimonio cultural

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ABSTRACT:

This work is a brief review of the state-of-the-art of photonics applications for the virtualization of cultural heritage, focusing mainly on 3D recording and digitization techniques, virtual reality and augmented reality. We show some LALFI-CIOp's contributions: the improvement of the resolution and accuracy of 3D reconstructions by using laser speckle and the combination of different imaging techniques, such as digital photogrammetry and Reflectance Transformation imaging; the development of low-cost systems to be used by museums; and virtual and augmented reality applications for dissemination of cultural heritage. Finally, we discuss an experience of transferring 3D digitization technology to several museums and cultural heritage institutions in Argentina and we propose an approach to extend the use of photonics in this field.

Key words: photonics in cultural heritage, virtualization, 3D, photogrammetry, augmented reality.

RESUMEN:

Se presenta una breve revisión del estado del arte de las aplicaciones de la fotónica para la virtualización del patrimonio cultural, centradas principalmente en técnicas de registro y digitalización 3D, realidad virtual y realidad aumentada. Se muestran algunas de las contribuciones del LALFI-CIOp. Estas son: el mejoramiento de la resolución y la exactitud de las reconstrucciones 3D mediante el uso de speckle, o la combinación de fotogrametría con Structure from Motion e imágenes por transformación de reflectancia; el desarrollo de sistemas de bajo costo para su empleo en museos e instituciones culturales y aplicaciones de realidad virtual y aumentada para la difusión del patrimonio cultural. Finalmente, se discute una experiencia de transferencia de la tecnología de digitalización 3D a varios museos e instituciones de Argentina y se presentan algunas propuestas para ampliar el uso de las tecnologías de la luz en este campo.

Palabras clave: fotónica y patrimonio cultural, fotogrametría 3D, virtualización, realidad aumentada.

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1. Photonics technologies in cultural Heritage

The use of photonic technologies in the field of cultural heritage has experienced a steady and substantial improvement. Their main advantages are that they are non-invasive, fast, repeatable, precise, and in many cases appropriate for in situ analysis. The work in this field has concentrated mainly on these areas: laser cleaning treatments for preservation of objects; development and application of techniques for, among others, diagnosis of the state of objects, characterization of the composition of materials, identification and authentication of pieces; and recording of images and their processing, especially in 3 dimensions, for documentation, dissemination and virtualization purposes.

The first works on the application of lasers in heritage conservation date back to 1973 and were initiated by J. F. Asmus. In these works, holographic techniques were used to determine the state of conservation of Venetian sculptures and the effect of the interaction of the radiation of a pulsed ruby laser on stone and marble [1,2]. Since the 1990s, laser cleaning has been used systematically in the restoration of building facades and cathedrals [3]. The application of lasers in the cleaning of materials such as marble, plaster and stone is now well established. Its success in these applications is largely based on the "self-limiting effect" that occurs in these materials since, its surface is white or less dark than the dirt, the fluence required to ablate the last one is much lower than that required to damage the substrate [4]. In the case of other materials, such as metals, glass, paper, etc., systematic studies are required to characterize the thermal photochemistry and photomechanical interactions involved in these processes, as well as the optimization of the laser parameters used (laser pulse duration, wavelength, fluence). These parameters and the specific properties of the material directly influence the action that the radiation can have on the surface [5,6].The laser cleaning technique has also been used in paints since the 90's of the last century, to remove varnish, pigments and dirt with obvious noncontact advantages over manual or chemical techniques [7].

On the other hand, there are several photonic techniques used for diagnostics and monitoring. These include Raman spectroscopy and its variants, for example, for the identification of inorganic and organic pigments, binders and varnishes [8]; Fourier Transform Infrared Spectroscopy (FTIR) for the analysis and identification of resins, starches and proteins [8]; Laser Induced Fluorescence (LIF) for the compositional analysis of molecules, visualization of under-drawings and assessment of past conservation treatments [9]; Multispectral and hyperspectral imaging to date and authenticate a painting, for analysis of paint layers and for the determination of the state of conservation of an art work [8]; Laser Induced Breakdown Spectroscopy (LIBS) for the identification of the elemental composition of materials [10]; Optical Coherence Tomography to detect cracks and other mechanical deterioration [8]; Digital Holographic Speckle Pattern Interferometers (DHSPI) to reveal subsurface anomalies, highlighting where consolidation treatments should be applied or how an object reacts to cleaning actions [8]; Laser Interferometry for structural diagnostics and to analyze deformations, deterioration and fracture mechanisms to assess the structural condition of materials and pieces [8]; and photothermal methods for nondestructive analysis of multi-layer structures [11].

There are few conservators and museologists trained in these techniques, even fewer in Latin America, where there are practically no museums or heritage institutions that use them. Consequently, the work in this field is mainly carried out through collaborations with research institutes and university groups specialized in optics and photonics. Since 1999, the *Laboratorio de Ablación Láser, Fotofísica e Imágenes 3D* at *Centro de Investigaciones Ópticas* (LALFI-CIOp) has been a pioneer in Latin America in researching the application of photonic techniques to the preservation of cultural heritage. This laboratory has applied laser cleaning in conjunction with traditional cleaning methods to remove corrosion, surface dirt, and classification marks on materials such as documents, glass, fabrics, metals, leather, and archaeological bones [12-16]. Additionally, Laser-Induced Breakdown Spectroscopy (LIBS) has been applied to determine trace elements in Homo sapiens teeth [17,18], and to characterize the composition of underwater archaeological objects and other archaeological pieces [19,20].

Regarding 3D imaging applications we present in this work a brief review of the state-of-the-art of photonics for the virtualization of cultural heritage, focusing mainly on 3D recording and digitization techniques, virtual reality, and augmented reality. Additionally, we show some new developments performed by LALFI-CIOp.

2. 3D recording and digitization techniques for cultural heritage

3D digitization or 3D reconstruction is the recording of the geometric structure and spectral signature (color) of three-dimensional physical objects. 3D digitization, in its typical and most widespread use, results in the creation of structures (meshes or point clouds) empty inside [21].

The motivation for 3D digitization in cultural heritage can be diverse. Among them are those related to research, conservation, and documentation. These include the study of the conservation state, the recording of deteriorations, details, or cracks that are not detectable by the naked eye, monitoring the deterioration over time, virtual mapping of deterioration and restorations, and obtaining measurements of the entire object or any segment the user wants to take without handling the object [22-25]. 3D reconstructions could also be used for restoration projects, either as a guide during the process or as a virtually restored substitute for the original material [26-28]. Regarding packing, shipping and exhibition, 3D digitization can be used to design supports and containers with specific measures and to create scale replicas [29]. For disseminating collections, 3D reconstructions can be uploaded to digital repositories, providing virtual access to researchers, students, and the general public. These reconstructions include object data and can be viewed from all angles, eliminating the need to handle physical objects or to visit the institution [30]. They can also support rich interactive multimedia presentations, for educational purposes [31]. Digitization also allows the virtual integration of collections that have been separated by geography and time [32].

All these studies require high-accuracy 3D models and, in many cases, high resolution. There is a wide variety of systems and techniques used for 3D digitization, leading to variations in their application, practice, workflow, and results [33-42]. Some of these systems require complex and expensive equipment, while others depend mainly on algorithms and software solutions. Similarly, techniques can be based on different types of detection, such as visible light, infrared, controlled lighting, or contact with objects. In the field of art and cultural heritage, the most used techniques are Laser and Structured Light Scanning (LS and SLS) based on triangulation and digital Photogrammetry with Structure from Motion.

Laser scanning is a non-contact measurement technique that allows the acquisition of three-dimensional information from the surface of an object illuminated by a laser beam. Time-of-flight based scanners are used for long range sensing, while triangulation based systems are useful for distances of less than 10 m, due to the gradual spread of the beam with distance and the limited resolution provided by the image sensor. Alternately, in structured light scanning, a pattern of non-coherent light fringes is used and the displacement of all of them is recorded at the same time [33]. 3D scanning devices (triangulation, or time of flight) vary in the range of reach, size and type of object to be scanned and the technology involved (i.e. laser, structured light with LEDs or white light).

Affordable commercial scanning systems have some limitations. On one hand, to obtain a complete 3D mesh it is necessary to perform several scans from different angles, and then align and merge them, resulting sometimes in errors in the final mesh. Also, these systems often include a camera to capture the color of the object's surface; this functionality requires synchronization and calibration to map the texture to the recorded geometry, which depends on the quality of the devices. Lastly, commercial systems are often outside the reach of most public cultural institutions, such as Latin American museums.

Photogrammetry enables obtaining geometric information of objects or scenes by using two or more photographs captured from different positions. This technique, which can also be used to generate maps, mosaics, orthophotos (i.e. photos without perspective distortion, widely used in cartography and architecture) and terrain elevation models, has evolved to produce computational results such as *point* *clouds*. Traditional methods required knowing the location of key points on the object and the position of the camera. Computer vision photogrammetry, based on a set of algorithms called Structure from Motion (SFM) is currently the most used method to obtain a 3D reconstruction in a fast and automatic way. It generates a 3D point cloud of the scene from a set of multiple images taken from different points of view with respect to the object [27,43-46]. This point cloud can be converted into a 3D textured mesh.

In the field of cultural heritage, SFM photogrammetry has been used for the documentation and virtualization of large objects and scenes, such as archaeological and architectural sites. In the last ten years, SFM photogrammetry began to be used for recording objects on the centimeter and millimeter scale and with more complex geometries. This was thanks to the development of advanced image processing techniques, which allow it to record objects with the same quality and resolution as conventional scanning techniques, but in a simpler way and at a lower cost [34,47,48]. It does not require a complex system (a camera and a computer with a suitable graphic card is enough) and can be easily implemented by museums' staff who have not been previously trained in image processing techniques.

There are many SFM software systems, either commercial, open source or free. Currently, the most used for 3D reconstructions of heritage objects are Agisoft Metashape, MeshRoom and COLMAP. Figure 1 shows recent results obtained by the authors of this work that compare the meshes obtained with COLMAP+OpenMVS, Meshroom, Colmap and Agisoft. As can be seen, COLMAP+OpenMVS and Meshroom bring a better result in terms of quality of the mesh than that obtained with COLMAP alone and Agisoft. Geometric measurements, above 0.7 mm, performed in centimetric objects, show that the 3D meshes generated by COLMAP+OpenMVS and MeshRoom have an accuracy greater than 97% using as reference the real object. In the literature there are other studies that compare these pieces of software in terms of the quality of the clouds, 3D meshes and textures obtained, as well as the processing times and algorithms involved [45,49-54].

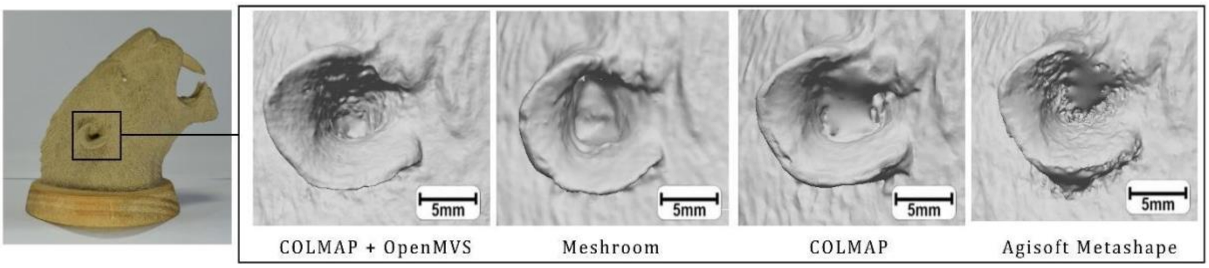

Fig. 1. Comparison of the meshes obtained with Colmap+OpenMVS, Meshroom, Colmap and Agisoft Metashape of a detail of a tiger's head replica.

In regard to the limitations of SFM photogrammetry, it can be said that the quality of the 3D reconstruction depends on the existence of features in the surface of the object that can be detected. Such features are the changes in the chromaticity and the intensity of the light diffused or reflected by the surface of the object. Applying SFM photogrammetry to featureless surfaces can lead to incorrect matching between photographs due to uncertainty in identifying reference points and ultimately generate a low-quality 3D reconstruction. Many of the objects that museums need to digitize in 3D sometimes do not have the surface and geometric characteristics typically required to apply the technique (heterogeneous texture and opacity, to name a few), making 3D reconstruction difficult or impossible, either in the form of dense point clouds or meshes. These objects include, for example, those with shiny surfaces such as metals, smooth and monochrome surfaces, translucent materials such as glass or resins, and very small objects on a millimeter scale. Sometimes, these are also problems that cannot be solved with LS and SLS.

One of the tools that could contribute to providing solutions to the problem of surfaces without detectable features is the implementation of mapping with visible light and laser speckle (the latter provides a heterogeneous noise pattern and, due to the low cost of the instrumentation, required, it can be implemented in a system transferable to cultural institutions) [55-58]. The idea is to artificially reproduce a large number of features that can be detected by the algorithms currently used in digital photogrammetry with SFM [59], and that these features do not affect the materiality of the object being digitized. It should be noted that SLS systems are often used to record this type of smooth surfaces. However, the challenge is to develop a low-cost and versatile system using photogrammetry. A result obtained by the authors of this work shows the advantage of using speckle to perform a 3D reconstruction of a shiny metallic object that cannot be reconstructed using standard SFM photogrammetry. If the object -in this case, a *bombilla* (straw) used for drinking *mate*- is reconstructed with SFM it results in a point cloud with very poor density, which cannot be used for mesh reconstruction. On the other hand, figure 2 shows the 3D point cloud created with a set of images of the *bombilla* illuminated with a speckle generated by a CW green laser pointer of 100 mW and a diffuser.

Fig. 2. 3D point cloud reconstruction of a metallic *bombilla* (straw) obtained with SFM photogrammetry and laser speckle.

In regards to the application of photogrammetry on objects embedded in resins or behind translucent surfaces, the use of filters, cross-polarization and image processing techniques could be implemented to eliminate reflections and occlusions so that the features of the surface to be digitized can be detected by the SFM software [60-63]. Also, there are optical configurations that could solve the sharpness problems produced by the narrow depth of field.

Another technique for digitization of cultural heritage is Reflectance Transformation Imaging (RTI) [64]. RTI is a computational stereophotometric technique based on the acquisition and processing of images of a fixed object that provides information of the relief of its surface with a 2D image. The result is an interactive digital image of the object, which can be illuminated virtually from any direction. This technique makes it possible to reveal details of the object's surface that are not visible by direct observation or by standard photography, such as marks, cracks, changes in the relief, holes, etc. [65-67]. The most popular RTI software is the one developed by the Cultural Heritage Imaging organization [68], which is very accessible by the professionals of museums, heritage sites and archaeologists [69]. Thanks to its versatility and use of low-cost components, the standard system can be easily modified to suit new applications and techniques, such as the micro-RTI variant [70].

While the SFM photogrammetry technique has limitations when applied to reflective or completely smooth and monochrome surfaces, the RTI technique can be applied to a wide variety of surfaces, whether they are opaque, reflective, smooth, textured, monochrome or colored. The resulting RTI image typically has a resolution similar to that of the photos used as input (defined in units of length per pixel). In contrast, 3D reconstructions obtained by SFM photogrammetry tend to have worse resolution, typically more than one order of magnitude above the resolution of the original photo. The most common way to improve resolution is to reduce the distance between the camera and the subject, which means taking more pictures to cover the entire object and therefore increasing processing time.

Several works have combined RTI with 3D models [71-75]. Some of them aim to apply RTI images only to some sections of the 3D model to be displayed on interactive platforms; others focus more on overlaying many textures, including RTI normal maps, to analyze different surface features of objects. Some of these works have combined 3D modeling software systems (like Blender) and commercial photogrammetry software.

We propose that one of the most efficient ways to improve the resolution of 3D models is to replace the original *rasters* (images from SFM process already aligned) of the 3D scene, obtained with photogrammetry, with the normal maps of different perspectives of the object obtained with RTI [76]. An example of this idea is shown in figure 3. On the left, it can be seen a 3D mesh of a ceramic fragment of a pre-Columbian vessel from the north of Argentina, performed with photogrammetry. In the same figure, on the right, the same reconstruction but textured with the *rasters* of RTI images is shown. In this 3D model, the normal information obtained with RTI was incorporated as an attribute of the polygons of the 3D mesh resulting in a resolution enhancement. It is worth mentioning that, although normal maps can also be incorporated into meshes obtained with LS or SLS, this cannot be done automatically. The manual procedure would be subject to operator-caused errors and it takes a long time to get perfect alignment of textures and meshes.

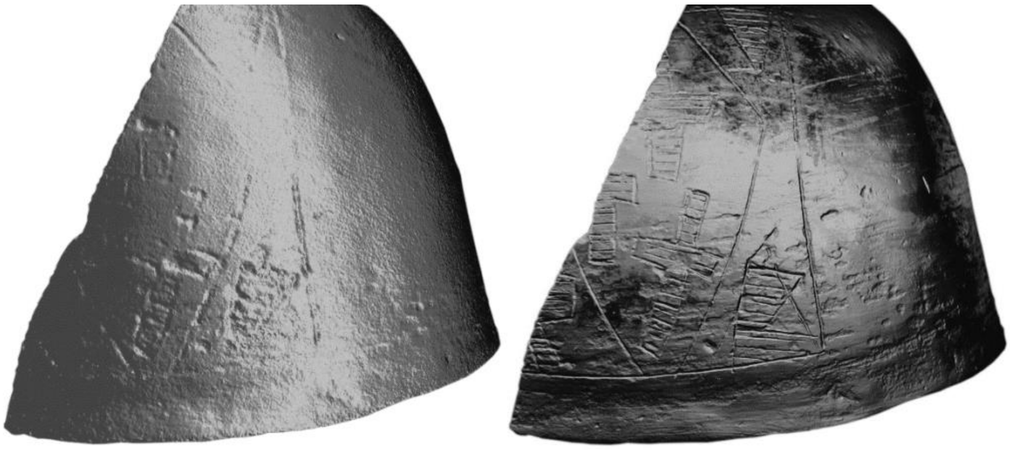

Fig. 3. Resolution enhancement of a 3D mesh by SFM + RTI. Object: ceramic fragment of a pre-Columbian vessel from the north of Argentina. Left: mesh obtained with SFM software. Right: Mesh obtained with SFM and textured with normals obtained by RTI.

3. Virtual museums and augmented reality

In recent decades, technology has played an increasingly important role in the dissemination and preservation of cultural heritage. Virtual museums, augmented reality (AR) and 3D reconstructions have emerged as key tools in this sense, offering visitors a more immersive and enriching experience.

The use of augmented reality technology in museums is becoming more frequent and diverse, and it offers various advantages. For example, it can give access to objects that are otherwise inaccessible because of their fragility. This is the case of an application used in the Sakıp Sabancı Museum in Istanbul, which allows the public to read all the pages of a series of books on display in a showcase on the second floor [77]. Another possibility is the combination of virtual and augmented reality to digitally recreate a specific environment. This is the case of “The Ara As It Was”, a project that uses a Samsung Gear VR device to show the 'Ara Pacis' monument like it was in ancient Rome, offering visitors the chance to experience immersive and multi-sensory environments [78].

Augmented and virtual reality can be used together with different 3D reconstruction techniques such as LS and SLS, SFM photogrammetry, Optical Coherence Tomography and micro-OCT, to assist in the creation of the 3D models. An example of this combination of techniques is the AR application called “Skin & Bones”, designed for the "Hall of Bones" at the Smithsonian National Museum of Natural History. This application offers visitors augmented reality content, videos and activities that complement the exhibition [79]. SFM photogrammetry can also be used to assist in the modeling of virtual reality environments. This is the case of a project carried out by the University of the Philippines-Diliman, in which the Bulwagan ng Dangal university museum was virtualized using photogrammetry, 3D modeling and augmented reality [80].

LALFI-CIOp has carried out several mixed reality applications (VR and AR) using captured reality and 3D modeling for the dissemination of argentine cultural heritage. “Virtual Collections”, one of those applications, depicts a virtual museum traveling on an asteroid through space. It consists of a total of twenty digitized objects, mostly by staff from the museums where the original works are located (see fig. 4). It includes an archaeological cave inside the museum (see fig. 5), which is an interesting possibility brought by virtual reality. This virtual tour is one of the results of a 3D technology transfer project to regional museums of the Province of Buenos Aires, Argentina [81]. The application was developed in the Unity game engine and there are three versions: a fully immersive one using a Head Mounted Display (HMD), a native one for desktop and an online one, published on the LALFI-CIOp website [82]. In the same way, the virtual tour "Krause: Vestigios disponibles” was developed, which consisted in digitizing a real itinerant exhibition of the work of the architect Vicente Krause, using modeling and captured reality 3D reconstruction techniques [83].

Fig. 4. A view of the virtual tour "Virtual Collections".

Fig. 5. A view of the 3D reconstruction of a prehispanic cave in the Province of San Luis, Argentina, obtained with SFM photogrammetry and displayed on the virtual tour "Virtual Collections".

Another of the applications developed by the LALFI-CIOp in relation to virtual tours is the 3D reconstruction of the tomb of Amenmose, in Luxor, Egypt. The walls inside the tomb were recorded with SFM photogrammetry and modeling is being worked on in Blender in order to develop an immersive virtual tour [84].

In regard to AR, LALFI-CIOp has developed two applications named "*MusAR*" and "*Los pañuelos siguen rondando*", both built for Smartphones [85]. The first one is an interactive app that allows for the visualization of virtual 3D museum objects through pattern detection on cards. Technologies such as Easy AR, Unity, Processing, and generative code were used for its development. The second app is a web experience in which users can interact with a geolocated augmented reality environment. This environment was designed to commemorate March 24th, National Day of Remembrance for Truth and Justice in Argentina. It is composed of virtual headscarves moving around in selected real environments such as several public squares of different cities of Argentina. Figure 6 shows a screenshot of the image rendered with this app when the user is pointing to the pyramid in the Civic Square of Ushuaia, Argentina.

Fig. 6. Screenshot of the visualization of the app "*Los pañuelos siguen rondando"* in the Civic Square, Ushuaia, Argentina

Geolocated augmented reality can be used to create outdoor exhibitions. An example of this is shown in figure 7. It is a web application that seeks to create an artistic exhibition, developed in collaboration with the artist Marcela Cabutti. The exhibited artworks depict various landscapes of Balcarce (Buenos Aires - Argentina) and were painted by local women artists (see fig.7). The geographical territory used is a trail in the mountain range of the same city, from where many of those landscapes can be seen. In this case, the technology is used as a tool to generate the poetic gesture of returning the works of art to the space they represent.

Fig. 7. Images created using augmented reality in the mountain range of Balcarce, Buenos Aires, Argentina. The artworks were painted by female artists from Balcarce.

4. From the lab to the museum

Despite the fact that these technologies are widely used internationally, in Latin America and, particularly, in Argentina, public museums do not have access to the latest techniques for digitization, documentation and analysis of the materiality of objects. In most cases, these museums do not even have a web page or their collections photographed for public access. In this context, the staff of LALFI-CIOp began a project in 2017 in collaboration with the Department of Cultural Heritage of the Province of Buenos Aires, a public institution on which several museums of the province depend. In the frame of this project, training courses, performed in LALFI's labs, for the staff members of seventy museums were carried out, and the software systems for the digitization of their collections were provided. As a result of this transfer, these museums have started to digitize in 3D part of their collections. A digital repository was created for giving access to these virtual collections. Part of this repository is online for the general public and allocated in the LALFI-CIOp's website.

It is important to highlight that the development of technologies for the 3D reconstruction of heritage objects is not only focused on the creation of specialized software, but also on simplifying the process for end users. An example of this is the Mu3D system that was developed by LALFI-CIOp. It combines the COLMAP and OpenMVS pieces of software in a single tool with a friendly graphical user interface for museum staff. This system simplifies the acquisition of the point cloud, the creation of the corresponding dense mesh, and the application of texturing to the 3D model, with just a few clicks. Mu3D is available at no cost for museums in Argentina [45].

The 3D models obtained with Mu3D weigh around 100 Megabytes, have a resolution of approximately 200 µm and an accuracy of more than 97% with respect to the real object. These features are suitable for documentation of deterioration, virtual restoration and dissemination. When applications aim to promote cultural dissemination, a viable approach is to use a high-resolution texture and simplify the mesh with another 3D image processing software system like Blender (fig. 8, on the left).

In the cases of large-scale digitization of objects, the combined recording of the photographs taken with a drone from the top, of the upper part of the object, and those obtained manually with the DSLR camera near the ground, was carried out. Figure 8 on the right shows the digitization of a 3m high historical meteorological booth recorded by using this method.

Currently, we have a project in progress that consists of the creation of a Laboratory of Multimedia Technologies in the mentioned Department of Cultural Heritage. This lab will be used for the virtualization and dissemination of the collections of the museums of the province of Buenos Aires.

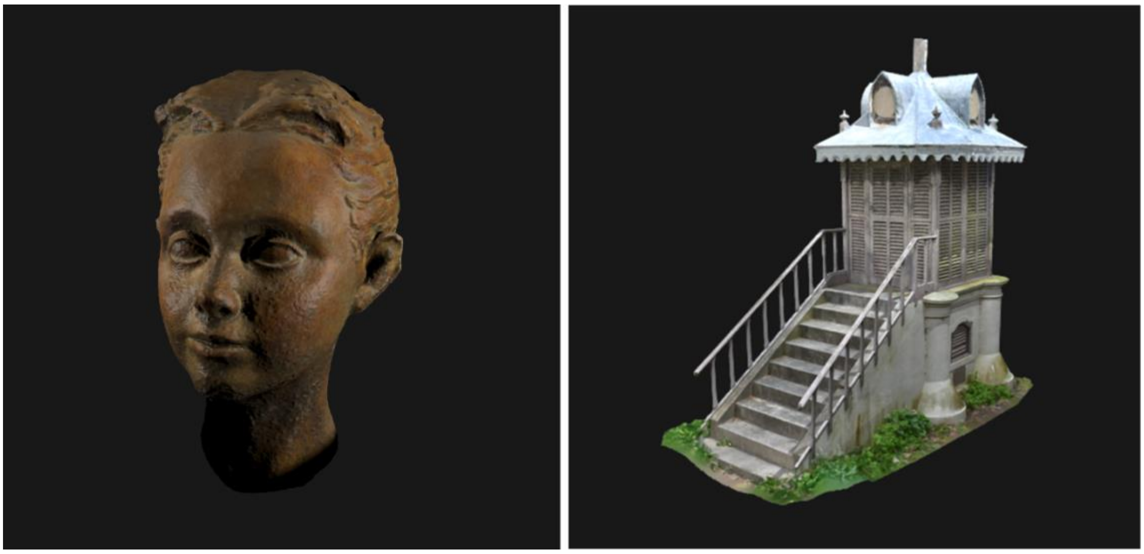

Fig. 8. 3D reconstructions obtained with the Mu3D system. Left: 3D textured mesh of a sculpture by Marta de Bellocq, "Cecilia", from the E. Pettoruti Provincial Museum of Fine Arts, La Plata, Argentina. Right: 3D textured mesh of a 3 m high historical meteorological booth of the Faculty of Astronomical and Geophysical Sciences of the National University of La Plata.

5. Conclusions

In this work we show the possibilities and potentialities of SFM Photogrammetry, RTI and mixed realities (virtual and augmented realities) for the dissemination and preservation of cultural heritage. The improvement in resolution and accuracy of these 3D recording systems will not only have an impact on the field of cultural heritage and museums, but also in other fields such as industry and production.

In the case of museums, it is important to note that 3D digitization must be subordinated to the objectives and the cultural project of each institution. For example, one goal may be to digitize a sculpture in 3D to record the deterioration before intervening in a restoration project. Another could be to design supports and packaging. A different one, could be the dissemination of it on a public website. In each case, the resolution and accuracy required of the final model may be different and may, or may not, be relevant to other aspects such as historical and artistic information.

As for the new developments in augmented reality, this technology allows the creation of ubiquitous virtual objects that can be accessed at the same time, from anywhere in the world. In this sense, virtual objects can be used as instruments for the dissemination of ideas and knowledge that we humans associate with them. Currently, we are actively engaged in the development of an augmented reality application with the aim of democratizing access to museum collections. This innovative approach to disseminating cultural heritage has the potential to popularize selected artifacts or works of art, thereby enhancing the museum's outreach and impact.

Something that we propose to take into account is that the new technologies can democratize access to cultural heritage if they are used within the framework of inclusive and participative public policies, open to the entire community. The access of museums and cultural institutions to them, and particularly to the photonics ones, should be part of a public cultural policy of each country, which would allow them to have a larger budget and more resources.

Finally, the photonics and optics laboratories that form part of the science and technology systems, should be encouraged to develop affordable and user-friendly techniques and instruments to be applied in the field of cultural heritage. Also, training of museum staff in new technologies is necessary. In addition, a closer interaction between laboratories and museums should be stimulated by creating interdisciplinary groups that can address the problems and demands that arise in museums and cultural institutions.

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