Virtual Archaeology Review

Sampled 3D models for Cultural Heritage: which uses beyond visualization?

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Resumen

Se puede afirmar que las tecnologías digitales han alcanzado un punto de madurez suficiente como para producir réplicas digitales de alta calidad del patrimonio cultural, especialmente de artefactos. Los resultados de la investigación producidos en la última década han mostrado una impresionante evolución y consolidación de las tecnologías utilizadas para la producción de modelos digitales 3D de alta calidad (escaneado 3D) y para el renderizado de esos modelos a una velocidad interactiva. En este sentido la tecnología es hoy perfectamente capaz de empujarnos a ir más allá de la simple visualización de los bienes culturales, hasta elaborar nuevas herramientas capaces de ampliar nuestra visión y capacidades de intervención así como de revisar los procedimientos actuales de investigación y gestión del patrimonio cultural. Este artículo presenta algunas experiencias recientes en las que modelos 3D de alta calidad han sido utilizados para mejorar la investigación, restauración y conservación del patrimonio cultural. Estos ejemplos constituyen una amplia revisión de los diferentes usos dados a los bienes culturales digitales tridimensionales.

Palabras Clave: *MODELOS DIGITALES 3D, ESCANEO 3D, PROCESAMIENTO GEOMÉTRICO ASISTIDO POR ORDENADOR RESTAURACIÓN.*

Abstract

Digital technologies are now mature for producing high quality digital replicas of Cultural Heritage (CH) artefacts. The research results produced in the last decade have shown an impressive evolution and consolidation of the technologies for acquiring high-quality digital 3D models (3D scanning) and for rendering those models at interactive speed. Technology is now mature enough to push us to go beyond the plain visualization of those assets, devising new tools able to extend our insight and intervention capabilities and to revise the current consolidated procedures for CH research and management. The paper presents a few recent experiences where high-quality 3D models have been used in CH research, restoration and conservation. These examples constitutes a broad review of different uses of digital 3D assets in the CH domain.

Key words: *DIGITAL 3D MODELS, 3D SCANNING, GEOMETRIC PROCESSING, COMPUTER-AIDED RESTORATION.*

1. Introduction

The evolution of the technologies for creating digital models of reality has been impressive in the last decade. The virtual representation of real or imaginary worlds is now a common resource in many application domains, with astonishing utilizations in entertainment industry. Even if most of those technologies have been developed for industrial applications (among others, rapid prototyping and movies), they find an ideal application to the Cultural Heritage (CH) domain. Most of the technologies developed for digital sampling the real world (we usually term them the *3D scanning*) can be used for producing digital 3D models of CH artefacts. Available digitization technologies allow to cover all the scale, from the smaller (a jewel or a small prehistoric stone tool) up to the larger artefacts (a building or an entire historical city). The evolution of acquisition devices has been paired with the improvement of sampled data processing and visual presentation technologies. Therefore, the advent of a wide availability of sampled 3D models might bring to the CH domain an impact similar to those brought at the end of 19th century by the advent of photography. Due to the introduction of low cost devices, of inexpensive 3D acquisition methods based on digital photography and on the advent of new capabilities to process 3D data and to get new insight (STANCO et al. 2011), the near future should bring a much larger diffusion and use of digital models in the CH domain.

So far, most of the CH applications have been limited to *visualization* over different media or platforms, e.g. desktop-based multimedia presentations, museums kiosks, or videos produced with computer animation. There is a general agreement that new visualization technologies have a paramount effect on our capabilities to disseminate CH knowledge. An easy example is education at all levels, that can increase the awareness of our common CH, allowing us to know different cultures and to help us in creating a common multi-cultural background.

Even if visualization has a great potential, producing just digital images is perceived as an intermediate goal by CH scholars and practitioners. They are questing to go beyond plain visualization, asking for new tools to assist research on CH by means of digital 3D models, for example to help assessing the conservation status or to plan and document CH restoration. The scope of this work, that is mostly based on a recent paper (SCOPIGNO et al. 2011) is therefore to present just very briefly the status of 3D acquisition and visualization technologies, to leave most of the space to the presentation of a few experiences that can show how we can use digital 3D models to affect the daily work of CH scholars, curators and restorers.

2. Digital 3D models - Acquisition and visualization

Technologies for the digital sampling of reality appeared around twenty years ago and consolidated in the last decade. A good survey is presented in (STANCO et al. 2011). The most well known approach is laser-based 3D scanning, that is often the subject of articles on the press or of television programs, but this is not the only approach available today. A full range of technologies is available, that differentiate either in terms of the sampling methodology or of the sampling scale supported (how big could be the sampled volume and, usually accordingly, how dense is the sampling). 3D data can be sampled by adopting a scanning device or also by one of the recent image-based approaches (which return raw 3D data by processing set of images, looking for stereo-matching of feature points).

The improvement of the technology has been impressing since the Digital Michelangelo Project (LEVOY et al. 2000), that is usually considered a pioneering project in the CH domain. We have now much better resolution (number of samples and density of those samples on the measured surface), improved accuracy, faster acquisition time, largely improved post-processing instruments and, finally, a reduced cost of technology. Nowadays, 3D scanning systems are priced in the range 3,000 -100,000 USD, with the less expensive devices playing a very important role: opening the market to the wide public and increasing awareness on the potential and on technology know-how. Consequently, the availability of free software solutions is also an important asset. This is the case of both reconstruction systems based on images and multi-stereo matching (e.g. *Arc3D* *http://www.arc3d.be/*) and processing tools for raw sampled data (see for example the open-source *MeshLab* tool *http://meshlab.sourceforge.net/*).

The reduction of the cost of the devices and of the time needed for processing the raw sampled data are making 3D digitization an affordable action. While the scanning of a single statue took around one month of work ten years ago, a high-resolution and high-quality 3D model can be produced nowadays in a couple of days of work.

We should also look to the other side of the coin: are we able to visualize the huge digital models produced with 3D sampling devices? Models made of up to hundreds million triangles can now be rendered in real time on commodities PCs, thanks to the impressing progress of graphics processing units (driven by the video-game industry) and the efficient multi-resolution visualization methods developed in the last decade. Moreover, we are now ready to move those 3D data on the web (for example, endorsing the new WebGL standard, see *http://www.khronos.org/webgl/* and *http://www.spidergl.org/*).

3. Using 3D models in Cultural Heritage

Initially, the most obvious CH applications of 3D sampled data focused on different incarnations of visualization-oriented applications. Being able to present visually an artwork is valuable for several tasks and to different potential users (art scholars, restorers, students, tourists and ordinary people). Therefore, by a large extent visual communication is the most common utilization of digital 3D models in the CH domain.

With the attempt to go beyond naive visualization, several previous experiences (see for example (CALLIERI et al. 2004)) have already shown that digital 3D models can be used for two major tasks:

- **Studying artworks with digital 3D models** (and related processing methodologies). Given the availability of digital 3D models, we can devise new processes able to execute specific investigations directly on the digital replica. Here the availability of a digital clone and of innovative modelling and shape-based analysis methodologies might allow us to gather new knowledge and new insight.
- **Digital 3D models as a support medium for indexed archival of knowledge.** The knowledge gathered from the different studies and analysis undertaken on a work of art can be mapped, annotated, indexed, retrieved, visualized, compared by means of the use of digital 3D models.

Another important distinction is among visual media used for story-telling purposes (e.g. animations produced to present a virtual reconstruction) and visual media used to increase knowledge or to provide quantitative experiences/insight. In the second case, the high accuracy of the digital model is basic requirement for any serious work: the level of *accuracy* satisfied by a given digital 3D model is a parameter of basic importance. This implies that models have to be produced adopting a *sampling-based* approach and, moreover, that digital data have to be paired with provenance data. *Provenance data* is of paramount importance in any scientific process or research, since it is crucial to document how a digital model has been created and up to what extent it can be considered a good representation of the real artefact. Provenance data should include complete information on the technology used to produce the digital model (sampling device used, specs of the sampling campaign, software used to process the sampled data, complete specification of all the post-processing filters used over the sampled data).

We cannot propose here a comprehensive presentation of all major experiences done in the last few years on this domain. Conversely, we present briefly just a few examples of enhanced use of 3D data either for improving knowledge or for offering enhanced opportunities for data presentation and integration.

4. Studying artworks with the help of the digital 3D medium

Digital 3D models would allow scholars to study artworks on a much wider scale than in real life, since the availability of good digital 3D models can allow scholars to dissolve the space and time constraints (e.g. virtual "hands on" experience on object located far away, no more time limitation due to museum working time and access rights). A crucial requirement for imposing digital models as the modern replacements of printed materials is the availability of: enhanced searching over digital libraries; interactive visual analysis (possibly, with no compromise on model accuracy and quality); flexible tools for shape comparisons and improved shape reasoning capabilities. With the potential of current technologies, this can be much easier accomplished in a connected web-based environment than in the real word. The integration of different media and the availability of good, searchable metadata and provenance data is a must to envision the digital library of the future.

A first step in this sense has been performed with the design of the CENOBIUM syste, designed in 2006 as a pioneering example of integration between textural descriptions, high-resolution images and 3D models (CORSINI et al. 2010). The CENOBIUM goal was to provide art scholars with a resource for studying Medieval sculpture by means of digital multimedia representations, at the highest level of quality available but in a very open approach. All the results of the digitization process (high-resolution images and high-resolution 3D models) are thus made available for remote consultation, by means of easy to use tools. The CENOBIUM web site (http://cenobium.isti.cnr.it) provides an integrated access to those different media. It is therefore possible to analyze and compare visually in a coordinated manner images or 3D models at full resolution (see Figure 1).

Searching is an important component in this vision. Even if shape-based search methodologies have evolved considerably in the last few years, we are still far from the performances expected by CH scholars: it is thus not sufficient to recognize a vase from a chair. More advanced characterization methods are needed, which should be able to discern between similar objects and, ideally, to characterize even the workshop of provenance.

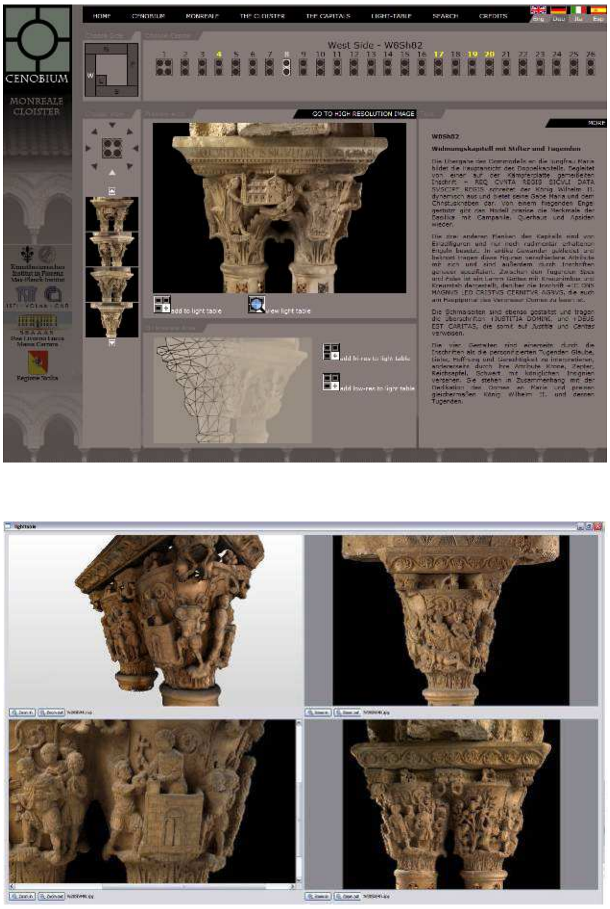

Fig. 1: The CENOBIUM web system, supporting visual access to medieval cloister sculptures. The web page presenting the data available for the single capitol is presented in the image above, while an interactive inspection session (three photographs and a 3D model) is in the image below.

An example of a shape comparison project concerned the evaluation of the attribution of a bronze horse statuette, conserved at the National Archeological Museum in Florence and attributed to Benvenuto Cellini (DELLEPIANE et al. 2007). The goal here was to find some numerical shape-based evidence to the similarity noticed with a Leonardo's metal-point drawing (RLW no.12358, Windsor Royal Collection). We confronted the two artworks by devising a shape-matching experiment between the 3D-scanned model of the bronze horse and the digitized 2D drawing (see Figure 2). The shape comparison was based on a technology that allows register a photo (or a drawing, as in this case) on a 3D model, following tightly the perspective projection rules. The results of the matching were extremely good, demonstrating that the drawing could have been produced from the bronze statuette by using some sort of camera obscura from two different points of view (the horse body and three legs in the drawing come from a first orientation, while the front-most leg and the head are traced according to a second position).

Fig. 2: We used geometric processing to estimate the shape similarity between two artworks, a bronze horse statuette and a drawing, and to find evidence for a new attribution hypothesis.

Another more recent experience with shape-matching, still in course of development, is the study of the *residual traces* left by carving instruments over unfinished Michelangelo's sculptures. We aim at a new methodology to perform the characterization and comparison of unfinished carved surfaces that still maintain traces of the carving process and of the instruments used. The final goal is to have more evidence and knowledge to get new light on the artist's sculpting procedure and, eventually, on some disputed attribution hypothesis.

Methods for visualizing and measuring residual traces have been developed in the framework of the Digital Michelangelo Project (LEVOY et al. 2000). The classical approach experimented so far in the digital domain has been to produce accurate digital 3D models of the artefact and to work with cut-through planes and with the corresponding section lines produced. Those section lines give us some information on the depth and the 2D shape of sections of the residual chisel traces. Main issues with this approach are that the selection of those cut-trough planes is not easy and, more important, it is a subjective choice. Section lines represent only a partial representation of a given chisel mark. Moreover, since the surface regions to be compared have different basic shapes, this make very complex also the comparison of the extracted section lines.

Conversely, we are working on an approach where a new "digital instrument" should allow the CH expert to make measurements and comparisons in a radically new way. Our idea is to design a new methodology based on the following three major ideas:

- At the level of the digital 3D representation, split the basic shape description (the overall shape of the sculpture) from the high-frequency detail corresponding to the remains of the chisel marks (the shape detail over the statue corresponding to just the traces of the sculptor's carving tools).
- Encode the high-frequency detail using a mapping from 3D space to 2D space, thus encoding with images the chisel marks shape detail. We maintain at the same time full control over the metric information encoded in the 2D image (since image gray levels are directly proportional to the depth of the chisel marks and are encoded in a known scale) and the accuracy of this encoding transformation (a pre-requisite is that the 3D-to-2D mapping transformation should be as much as possible isometric).
- Finally, design new tools for performing easy comparisons and analysis of the traces over and among the 2D representations. These tools will work on the 2D representation and will be sufficiently flexible to allow the CH expert to compute several different types of measures and matches.

5. Supporting documentation for on-site archaeology

Archaeology has been a pioneering domain for the use of digital technologies. Excavations require a sophisticated representation of the destructive digging process and of its intermediate results and findings. This originated, first, the use of Data Base Management technologies and, later on, an early adoption of Geographic Information Systems. In this domain, digital representations have been based so far mostly on 2D or 2D 1/2 spaces. Very few are the experiences so far going towards a real 3D documentation of the excavation process and of its findings.

Fig. 3: Four different 3D models showing the progress of an excavation (3D models produced with Arc3D and MeshLab).

On-site documentation of archaeology excavations is an ideal application domain for the new 3D sampling solutions based on *dense stereo matching* or *structure from motion*, due to their minimal hardware requirements (just a digital photo camera) and easiness of use in all environments. The availability of inexpensive 3D sampling solutions (e.g. the ARC3D web-based multi-stereo-matching reconstruction server coupled with the MeshLab processing tool) is a great advancement for a domain where low budget is the norm. Some issues inherent with this specific data sampling approach are that the quality of reconstruction can vary among scenes, and also inside a single scene, depending on factors related to the object (texture, scale of features, optical characteristics), but also on the environment (illumination, sharpness of photos, completeness of photographic coverage). Moreover, dense stereo matching data are usually generated with an unknown scale, and a scale factor is needed to bring the data in a usable 3D space.

Anyway, it has been demonstrated that those technologies can be proficiently used to document the excavation status on a daily time frequency, replacing the usual 2D images with 3D models (DELLEPIANE et al. 2011). The availability of 3D models that depict the status of the excavation opens a large number of different ways to monitor and analyze the progress: production of cut-through sections, computation of relative depths and distances, relocation of the findings in proper locations, production of high-resolution images, etc. The usually destructive excavation process can thus be recorded in its full space: *3D* plus *color* plus *time*, since we can to put in the same reference space all the acquired 3D models enhanced by photographic detail. Therefore, we can visualize spatial and temporal information at the same time (see Figure 3).

6. Supporting the restoration of fragmented artwork

Virtual reconstruction has been so far one of the most common CH applications of 3D graphics. The reconstruction of artefacts which are not existent anymore, using the available historical material (photographs, maps, drawing, knowledge) is a fascinating opportunity. In this domain, procedural reconstruction methods present a huge potential for the construction of realistic and navigable models of ancient monuments or even entire cities (DYLLA et al. 2009).

The focus of these technologies is not just to produce visual representations, but to allow us to experiment and assess different reconstruction hypothesis, thus helping us to increase the knowledge on the artwork.

3D technologies can also be proficiently used for either real or virtual reassembly of broken or dismantled artworks. An example is the restoration of the *Pietranico's Madonna* (a painted terracotta, XV cent., L'Aquila Museum, Italy). This statue has been severely damaged during a recent earthquake in central Italy, since it was fragmented in 19 large pieces and several smaller remains. In this case the goal was not just using digital 3D models to document the restoration project, but to actively contribute to the restoration with the definition and rehearsal of virtual reassembly hypothesis.

Reconstructing a fragmented artefact is a slow process usually performed manually by archaeologists or restorers, with several iterations of the cycle: fragments visual analysis - devising matching hypothesis - rehearsal by adjoining pieces. Checking matching pairs is a critical step, since the pieces are often fragile and holding together a few pieces (if not the entire reassembled set) is highly complex in the physical space. Restorers perform this action either by gluing/fixing the fragments or by building specific supporting structures. Moreover, the rehearsal and assessment phase cannot be done by just considering a subset of the pieces; we should build the entire puzzle to have a global view and a solid assessment of the hypothesis, which makes the job even more complicated. This makes reassembly a really complex and highly time consuming task.

Fig. 4: The digital assembly of the Madonna of Pietranico from the digitized fragments (image above) and the design of the two supporting elements (head and bust) created as digital shapes and then constructed using rapid prototyping for the real assembly.

Digital reassembly has been studied in several projects, focusing on reassembly of shreds of ancient pottery, statues, frescos, bas-relieves, etc. The adoption of a computer-aided approach can be requested in case of: extreme fragility of the artefact, complicated manipulation (being the fragments too heavy to be easily manipulated) or the very high number of shreds, that make the manual search extremely complex (a good example is the case of fragmented frescos, decomposed in a huge number of pieces (TOLER-FRANKLIN et al. 2010)). Most of the approaches present automatic matching solutions (HUANG et al. 2006), focusing on the shape properties of the shreds or, in some cases, by taking into account also the pictorial and decoration content of the pieces.

In the case of the Pietranico's Madonna, the virtual reconstruction was performed by keeping the CH experts in the loop. Conversely than adopting pure automatic solutions, we asked the restorers to show us all the matches they have individuated in the first analysis phase (based on fragments' shape, decoration, finishing, etc). Since the fragments were sufficiently small and lightweight to be manipulated by the restorers (even if with a lot of care to avoid further damages), we asked the restorer to hold each of these matching pairs in the adjoining pose and acquired a single range map of the two joined fragments. This single range map has been used to translate the fragments in the correct position in the virtual digital space (see Figure 4). While working on the digital space, we validated the matching pairs proposed by restorers, individuated some other matches induced by the initial ones (those new joins hypothesis have been communicated to the restorers and further checked with them), and finally made an overall validation of the entire graph of pair-wise matches and of the proposed re-assembly. the latter work was also done by comparing the results of the digital reunion with the available historical photos of the artefact.

Once a recombining scheme was agreed, the real physical reassembly started. A restoration goal was to avoid to simply glue the fragments, but to design and build a structure which should hold all fragments in their correct reciprocal position. Here again the availability of a digital model was helpful. The final supporting structure is based on two solid pieces that fill up the internal void space in the inside of the terracotta statue, i.e. the chest and the back of the head; these two pieces are connected by an iron bar and are used to hold and glue all the fragments. These internal filling components have been designed by using the digital 3D models of the reassembled fragments (see Figure 4) and have been produced by using rapid reproduction technology (3D printing). The design of the filling parts has been performed with MeshLab by reconstructing the shape of the internal void space bounded by the statue fragments. This resulting shape was then manually edited in order to correct small meshing problems (minor interpenetrations, protruding surfaces) and to remove some protrusions with the aim of facilitating the proper assembly of the fragments on top of the internal nucleus.

Another important issue in terms of virtual restoration is the study and visual presentation of the original aspect of archaeological sculptures or architectures. Due to the deteriorating effect of both time and human activities, most archaeological findings lost their original painted decoration or present severe deteriorations. The Pietranico Madonna lost most of the painted decoration and thus a digital restoration of its original aspect was also envisioned. This work resulted much more complex than expected. An extensive analysis of the original polychrome decoration done over the Madonna revealed a very complex structure: we had a base of preparatory plaster and several different layers of painted detail, including also the use of metal leaf (silver and gold) attached to the surface to increase the transparency and lightness of the painted decoration. Our plan was to produce a virtual restoration of the polychrome decoration over the digital 3D model, by using the painting features of the MeshLab tool. Two major problems emerged from this case study and clarified some limitations of the current technology:

- Thick layers of preparation material usually allow to have a basic surface that is much smoother than the raw terracotta surface; this means that we should be able to simulate the deposition of this thick layer, by changing the surface geometry (i.e. applying a material that has both tint and thickness, possibly in a progressive manner);
- Polychromy is usually implemented by the overlap of different pigments layers, in such a way that the final appearance is produced by the way the light interfere with those layers. This implies that an accurate simulation requires to encode explicitly the existence of those layers (possibly, encoding also the reflection properties of each of those materials) and not just the composition of different RGB values. The presence of metal leaf in some regions and an underground reflective layer makes this even more complex.

The results obtained with the current capabilities of MeshLab are shown in Figure 5.

7. Concluding remarks

This paper briefly presented some experiences where digital 3D models and geometry processing technologies have been used to support the work of CH scholars and restorers. Since we have very good and consolidated technologies for constructing digital replicas of works of art, it is now time to enlarge the offer of interactive tools based on visual computing technologies. Those new tools should become the instruments of the new millennium for CH expert or practitioner (archaeologist, scholars, restorers, students).

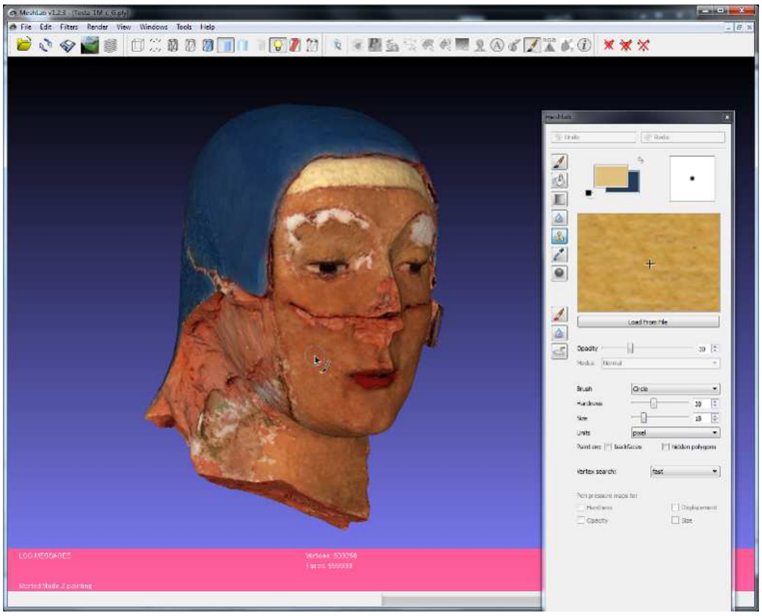

Fig. 5: A snapshot of MeshLab during the repainting of the head section of the Madonna.

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