3D Models for Cultural Heritage: Beyond Plain Visualization

Roberto Scopigno, Marco Callieri, Paolo Cignoni, Massimiliano Corsini, Matteo Dellepiane, Federico Ponchio, and Guido Ranzuglia

ISTI-CNR

Digital technologies are transforming the way cultural heritage researchers, archaeologists, and curators work by providing new ways to collaborate, record excavations, and restore artifacts.

The technologies for creating digital models of reality have undergone an impressive evolution. Although developed for industrial applications such as rapid prototyping and entertainment, these technologies are ideal for helping to preserve and restore cultural heritage (CH). For example, many technologies developed for digital sampling—usually called 3D scanning—are useful in producing digital 3D models of CH artifacts.[1]

The Digital Michelangelo Project pioneered the use of computer graphics in the CH domain,[2] and technology has continued to improve. Digitization can now cover artifacts ranging from the smallest (a jewel or a small prehistoric stone tool) to the largest (a building or an entire historical city), aiding researchers by providing much better resolution (as measured by number of samples and density of those samples on the measured surface) and improved accuracy. Acquisition time, postprocessing tools, and cost have also improved.

These technologies have the potential to truly advance CH, perhaps eventually having an impact similar to that of photography at the end of the 19th century. Such advancements, however, will only come with the wider availability of sampled 3D models. This in turn will require low-cost scanning devices and inexpensive 3D acquisition methods based on digital photography, such as the Arc3D webservice (www.arc3d.be). New open source resources to process 3D data, such as the MeshLab tool (http://meshlab.sourceforge.net), will also be key factors in achieving increased diffusion and use of digital models in the CH domain.

So far, most CH applications address visualization using various media or platforms: desktop-based multimedia presentations, museum kiosks, or videos produced with computer animation. Commodity PCs and, in the near future, Web streaming can render models consisting of tens of millions of triangles in real time. Researchers generally agree that new visualization technologies are of paramount importance in disseminating CH knowledge.

Despite visualization's potential, CH scholars and practitioners perceive producing digital images as an intermediate goal. The greater challenge lies in creating new tools that use 3D models to assist CH research, helping to assess conservation status or to plan and document restoration. Previous efforts have already demonstrated the usefulness of 3D models for two major tasks:[3]

- *Studying artwork.* Researchers can devise new processes for conducting specific investigations directly on digital replicas. Here, the availability of both digital clones and innovative modeling or shape-based analysis methodologies might lead to new knowledge and insights.
- *Serving as a support medium for indexed archival knowledge.* Researchers can use 3D digital models to map, annotate, index, retrieve, visualize, and compare the knowledge gathered from studies and analyses of artwork.

Rather than a comprehensive presentation of all recent efforts in this area, we present a few examples to show how digital 3D models affect the daily work of CH scholars, curators, and restorers.

STUDYING ARTWORK

Digital 3D models would let scholars study artwork on a much wider scale than in real life, since they could have virtual access to objects located far away, without the limitations of museum operating hours or access rights. A crucial requirement for using digital models as replacements for printed material is the availability of the following:

- enhanced searching over digital libraries;
- interactive visual analysis without compromising model accuracy and quality;
- flexible tools for shape comparisons; and
- improved shape reasoning capabilities.

Today, these requirements are most easily met in a connected Web-based environment. The integration of different media and the availability of reliable, searchable metadata and provenance is a must for future digital CH libraries.

The Cultural Electronic Network Online: Binding up Interoperable Usable Multimedia (Cenobium) project is a pioneering example that integrates textural descriptions, high-resolution images, and high-detail 3D models for CH.[4] The project's goal is to support art history studies by providing models and tools for the visual comparison of Romanesque cloister capitals in the Mediterranean region. Researchers have digitized three cloisters thus far and plan to digitize others.

The Cenobium website (http://cenobium.isti.cnr.it) provides integrated access to the different media concerning all the cloisters' capitals. As Figure 1 shows, the site handles such information through a database that interconnects access to the various media including text, images, and 3D models. One innovative contribution is the LightTable tool, which lets users select high-resolution documents to download and then identify the ones to visualize. It is therefore possible to analyze and visually compare images or 3D models at full resolution. A video available at www.computer.org/computer-multimedia illustrates the use of this tool.

Searching is also an important component. Despite the advances in shape-based search methodologies in the past few years, they still don't offer the performance that CH
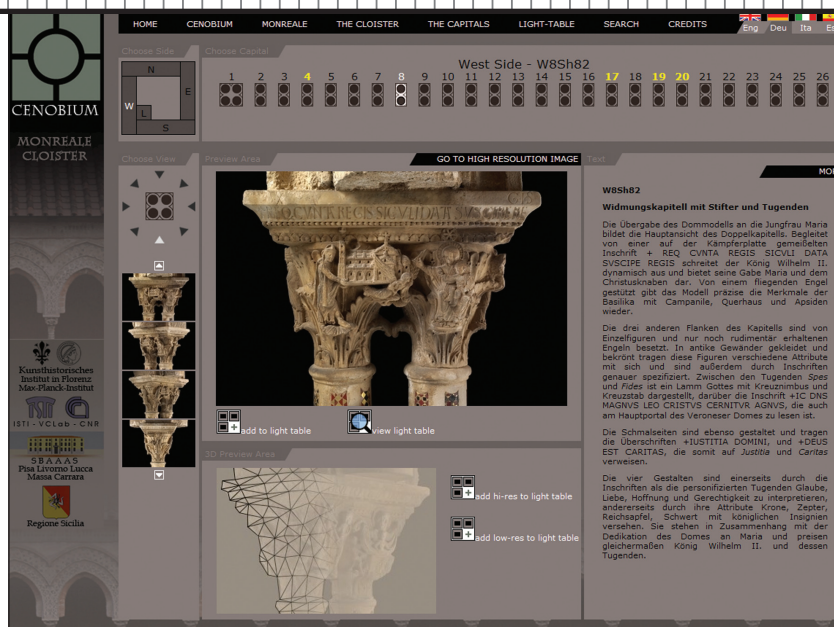

Figure 1. Cenobium project website. Screenshot of the integrated information about a capital on the west side of the Monreale cloister.

Figure 2. Example shape comparison between a bronze horse and a metalpoint drawing, showing how they match in a digitally produced perspective projection.

scholars expect. It is not sufficient for such applications to merely distinguish a vase from a chair. More advanced characterization methods must discriminate between similar objects and, ideally, characterize even the workshop of provenance.

As Figure 2 shows, an example shape comparison project concerned the attribution of a bronze horse statuette. Scholars attributed the statuette, conserved at the National Archeological Museum in Florence, to Benvenuto Cellini.

An art practitioner, Mark Fondersmith, noted a shape similarity with a metalpoint drawing by Leonardo da
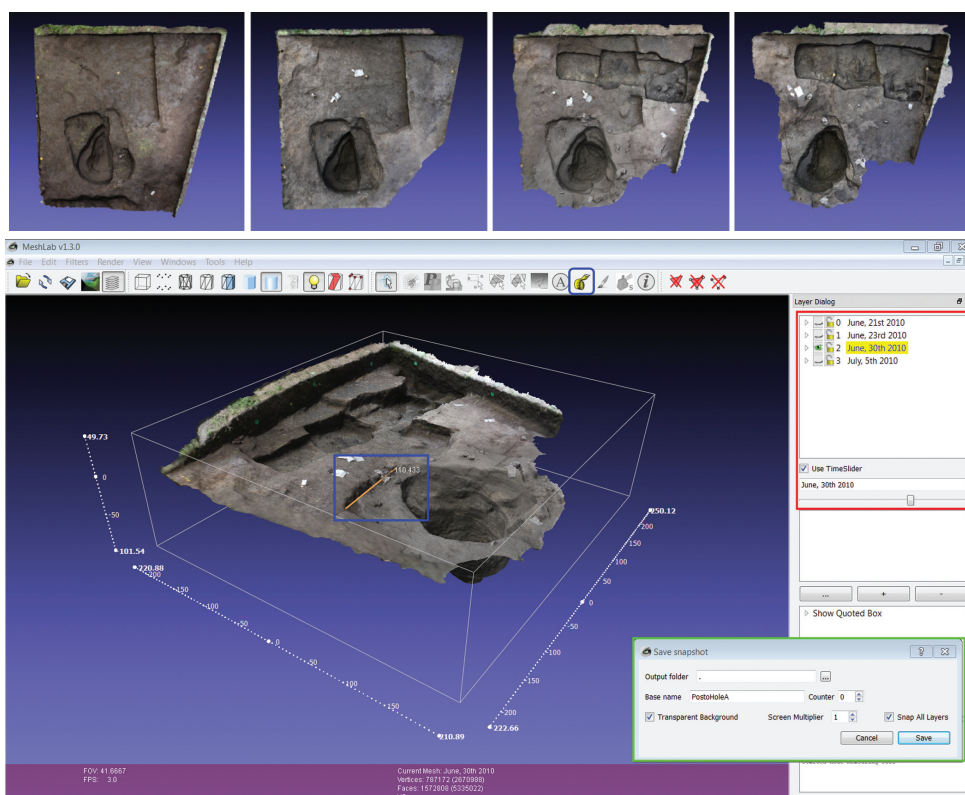
Figure 3. Snapshots of various time steps, produced with the canonical top view, showing the evolution of the excavation (upper images). The MeshLab snapshot in the bottom image provides a time slider and can display the length of any user-selected distance query.

Vinci (Royal Library, Windsor, no. 12358). We compared the two artworks by devising a shape-matching experiment between the 3D-scanned model of the bronze horse and a digitized copy of the 2D drawing,[5] basing the shape comparison on a technology that allows registration of a photo (or a drawing, as in this case) on a 3D model, tightly following the perspective projection rules. The match results 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: in the drawing, the horse's body and three legs come from a first orientation, while the frontmost leg and head are traced according to a second position.

This comparison opened up a controversy over the statuette's current attribution. If our hypothesis was correct—that is, that da Vinci (1452-1519 AD) was sketching from the bronze statuette in 1480, then Cellini (1500-1571 AD) was not likely to have been the sculptor.

Obviously, we cannot obtain a precise time estimate from a shape-matching test; physical dating technologies have been developed for that purpose. Neither does shape-matching provide a solid attribution hypothesis. However, this test assessed an embarrassing shape similarity, one highly unlikely to happen by chance. The dispute about this artwork remains unresolved.

DOCUMENTATION FOR ONSITE ARCHAEOLOGY

Archaeology has pioneered in the use of digital technologies because excavations require a sophisticated representation of the destructive digging process as well as its intermediate results and findings. Archaeologists employed database management technologies and, later on, adaptations of geographic information systems. So far, archaeology has relied on digital representations of 2D or 2D 1/2 spaces, which are an immediate derivation of the usual map-based representation. Very few projects thus far target 3D documentation of the excavation and its findings.

Yet, because of its minimal hardware requirements (just a digital camera) and ease of use in all environments, onsite documentation of excavations is an ideal application domain for new 3D sampling solutions based on dense stereo matching or structure from motion. The availability of inexpensive 3D sampling solutions such as the ARC3D Web-based multistereo-matching reconstruction server coupled with the MeshLab processing tool is a great advancement for a domain in which low budgets are the norm.

An inherent issue with this specific data-sampling approach is the quality of reconstruction, which varies among scenes and also inside a single scene, depending on factors related to the object such as texture, scale of features, and optical characteristics. The environment—illumination, photo sharpness, and completeness of photographic coverage—can also influence the reconstruction. Moreover, a scale factor is necessary to convert the data into a usable 3D space since dense stereo-matching data is usually generated with an unknown scale.

Researchers have demonstrated that it is possible to proficiently use those technologies to document excavation status daily, replacing the usual 2D images with 3D

models.[6] Having 3D models of an excavation's status opens up several different ways to monitor and analyze progress: production of cut-through sections, computation of relative depths and distances, relocation of findings in proper locations, production of high-resolution images, and so on. The usually destructive excavation process can thus be recorded in its full space: 3D *plus* color *plus* time, since the same reference space can record all the acquired 3D models enhanced by photographic detail. This permits researchers to visualize spatial and temporal information at the same time, as Figure 3 shows.

Figure 4. Reassembly of the Madonna of Pietranico: (left) a pre-earthquake photo; (right) a subset of the remaining fragments.

Finally, it should be possible to integrate all documents and knowledge atop the digital 3D model. This requires enhanced data-management systems that can link any type of media to the 3D model's corresponding point or region, thus georeferencing the available data. Such a system could further provide annotation capabilities, supporting easy, efficient visualization and inspection of the 3D model. These requirements are among the goals of the European 3D-COFORM project (www.3d-coform.eu).

RESTORATION OF FRAGMENTED ARTWORK

Thus far, *virtual reconstruction* has been the most common CH application of 3D graphics. Using available historical material such as photographs, maps, drawing, and expert knowledge to reconstruct artifacts that no longer exist is a fascinating opportunity. The focus of these technologies is not just to produce visual representations, but to permit the experimentation and assessment of different reconstruction hypotheses. These technologies thus increase knowledge rather than just producing visualization-related results.

Such 3D technologies can also assist with either real or virtual reassembly of broken or dismantled artwork. A good example of the first case is the restoration of the Madonna of Pietranico, a 15th-century painted terracotta artifact from the L'Aquila Museum in Italy. This statue was severely damaged during a recent earthquake in central Italy, when it fell to the ground and fragmented into 19 large pieces and several smaller ones. Restoration started in 2010; in this case, the goal was to use 3D models to actively aid the work by allowing curators and restorers to virtually test hypotheses and rehearse scenarios for reassembly. In this way, the models would actively contribute to the curators' and restorers' work rather than just document the restoration.

Reconstructing a fragmented artifact is a complex and time-consuming process usually performed manually by archaeologists or restorers in several iterations: analyzing visual fragments, devising matching hypotheses, and rehearsing the reattachment of adjoining pieces. Checking matched pairs is a critical step since the pieces are often fragile, and holding together a few pieces (if not the entire reassembled set) is a complex physical task. Restorers perform this action by either gluing or fixing the fragments or by building specific support structures. Moreover, they often start by just considering a subset of the pieces, but must construct the entire puzzle to have a global view and allow a solid assessment of the restoration hypothesis, further complicating the job.

Digital reassembly has been studied in several projects, focusing on reassembling ancient pottery, statues, frescos, bas reliefs, and so on. A computer-aided approach is ideal for extremely fragile artifacts, or those requiring complicated manipulation—for example, those having fragments too heavy for easy manipulation or having a high number of shards, which makes the manual piece-matching complex. A good example is the restoration of fragmented frescos, which can decompose into a huge number of pieces.[7] Most digital approaches present automatic matching solutions[8] that focus on the shape properties of the shards or that, in some cases, account for the pictorial content or decoration of the pieces.

Figure 5. Restorer rehearses the matching between two fragments, making it possible to acquire a single scan of the pose linking fragments C3 and C2.

For the Pietranico Madonna, we first scanned all major fragments, which ranged from large base pieces (60 × 40 × 50 cm) to smaller body fragments, as Figure 4 shows. We used a Konica Minolta VI910 laser scanner and processed sampled raw data using MeshLab. A photographic campaign produced a color mapping of the fragments during the scan.

Our team performed a virtual reconstruction, keeping the CH experts in the loop. Rather than adopting automatic solutions, we asked restorers to show us all the matches they had identified in the first analysis phase based on the fragments' shape, decoration, finish, and so on. Since the fragments were sufficiently small and lightweight for the

Figure 6. Scanned models of the fragments in the Madonna's uppermost section: (left) after digital reunion; (right) the complete statue after digital reconstruction.

restorers to manipulate (even if it took significant care to avoid further damage), we asked them to hold each of these matching pairs in their adjoining pose while we created a single-range map of the two joined fragments. Figure 5 shows one such match. We then used this map to transpose the fragments into the correct position in the virtual digital space, as Figure 6 shows.

While working in the digital space, we validated the matching pairs proposed by restorers, identified some other matches induced by the initial ones, and communicated those new join hypotheses to the restorers. Finally, we made an overall validation of the entire graph of pairwise matches and of the proposed reassembly. The work done thus far on the Madonna showed that focusing on only the automatic reassembly feature is not a proper approach; rather, it is important to keep the CH experts in the loop.

Once the restorers and our team agreed on a recombination scheme, the physical reassembly started. A restoration goal was to avoid simply gluing the fragments, instead designing and building a structure that would hold all the fragments in the correct position. Here again, the availability of a digital model was helpful. We based the final support structure on two solid pieces that fill the void (in the chest and the back of the head) on the inside of the terracotta statue; these two pieces are connected by an iron bar, holding or providing a gluing surface for all the other fragments.

We designed these internal fill components using the digital 3D models of the reassembled fragments, as Figure 7 shows, using rapid 3D printing reproduction technology to produce the components. To design the fill components, we used MeshLab to reconstruct the shape of the internal void space bounded by the statue fragments. We then manually edited the resulting shape to correct small meshing problems such as minor interpenetrations and protruding surfaces and to remove some protrusions. Doing so facilitated the proper assembly of the fragments on top of the fill components. Once reproduced with 3D printing technology, these components provided an excellent basis for the artifact's physical reassembly.

VIRTUAL RESTORATION OF PAINTED DECORATIONS

Another important issue in virtual restoration is the study and visual presentation of the original aspect of archaeological sculptures or architectures. The original painted decorations on most archaeological finds are either severely deteriorated or missing altogether. An example of the latter is the Pietranico Madonna. Curators would like to have a digital restoration of its original aspect because most of its painted decoration has been lost.
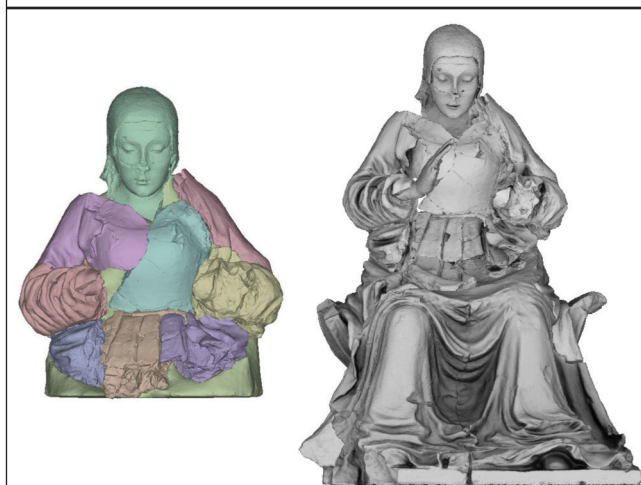
With the help of new optical, physical, or digital sampling technologies, it is possible to hypothesize about an artwork's original color by analyzing traces of the original pigments found on the surface via macrophotography, multispectral images, constituent material analysis, and so on. Thus far, researchers have presented their hypotheses by means of painted gypsum replicas of artifacts.[9] Digital 3D models would be a much more convenient medium: they are easier and more quickly "painted," and such models can serve as the basis for other visual presentation media, such as interactive visualizations and computer animation.

An example of 3D model repainting is the reconstruction of the original appearance of the terracotta statues from Luni's Temple;[10] Luni was first an Etruscan and then a Roman town in northern Tuscany, Italy. Figure 8 summarizes this project, which is first a reassembly problem; we still have many shards to include in reconstructing a complete frieze from the temple, which is much larger than the section shown in the figure.

Figure 7. Solid nucleus produced from the digital model to hold the fragments of the body section for the Madonna (upper left) and an image from the rear of the digital model, showing the assembly of the two nuclei (body and head) and the fragments (upper right). Restorers reassembled the statue by adding fragments to the fill components made with 3D printing technology (bottom).

We use residual traces to generate hypotheses about the original color of the painted surfaces. The preliminary result presented in the rendering in Figure 8 (right) shows the repainting of one statue, implemented over the digital 3D model using the painting features of the MeshLab tool. Figure 9 shows a MeshLab repainting session.

An interesting practical deployment of virtual repainting employs digital video projection rather than a physical replica. Using commodity video projectors, it is possible to virtually restore color to the original artwork by repainting the digital 3D model and projectin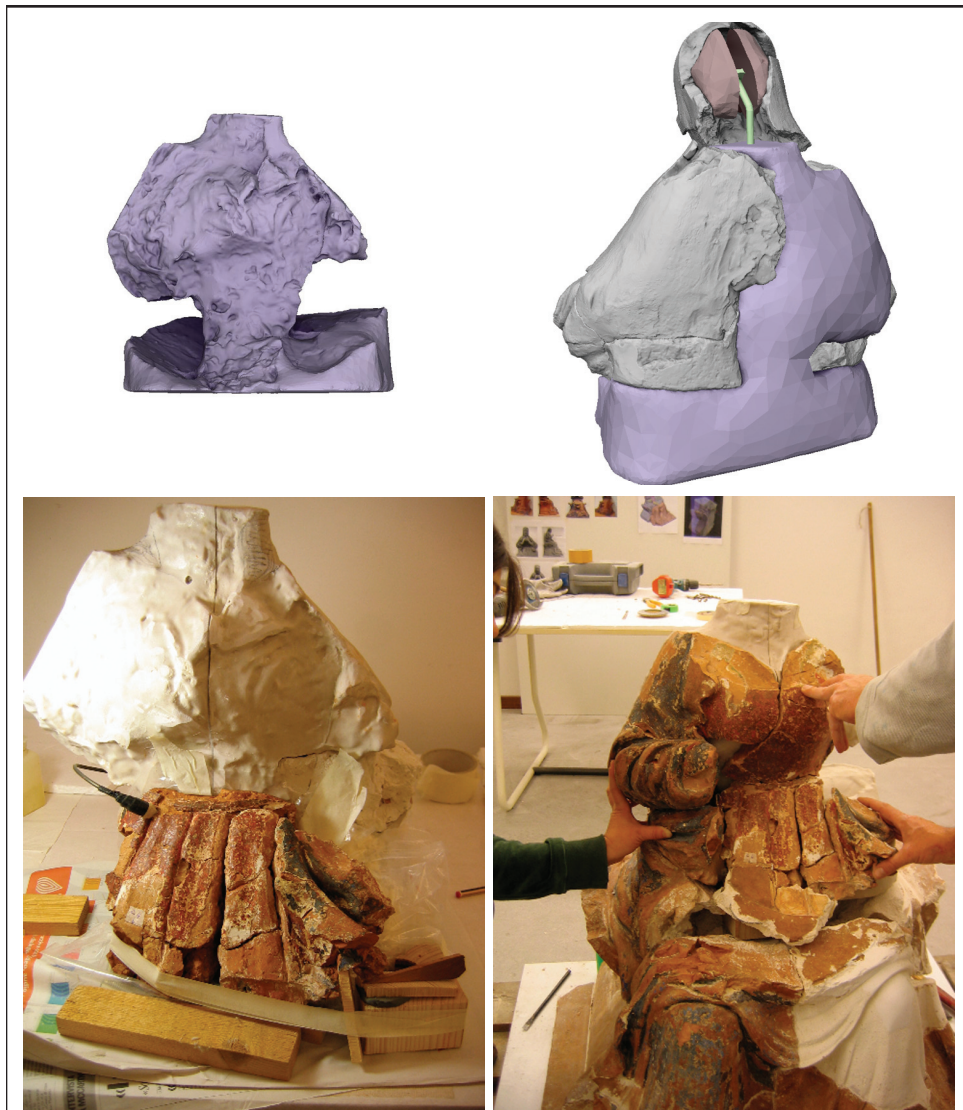g the model onto the original artifact's surface. An alternative is to project the model onto solid 3D copies of the artifact produced with rapid reproduction technologies. Researchers can use these approaches to quickly present different hypotheses for the original surface decorations.

A GLANCE INTO THE FUTURE

The available digital tools and those coming in the near future will significantly change the current organization of research, management, and conservation in CH. As in other scientific domains, digital tools can change the way CH scholars organize their work, not only by enhancing the presentation and dissemination of results, but also by affecting basic research methodologies. Digital instruments

Figure 8. Reassembly and virtual restoration of a fragmented artwork. (top) Physical recomposition of a small subset of the fragments of the Temple of Luni. (bottom, left and center) Two renderings of a digital model of one statue, first with and then without the current surface color, produced by mapping photographic detail. (bottom, right) Statue colored in hypothetical original colors, based on trace evidence.
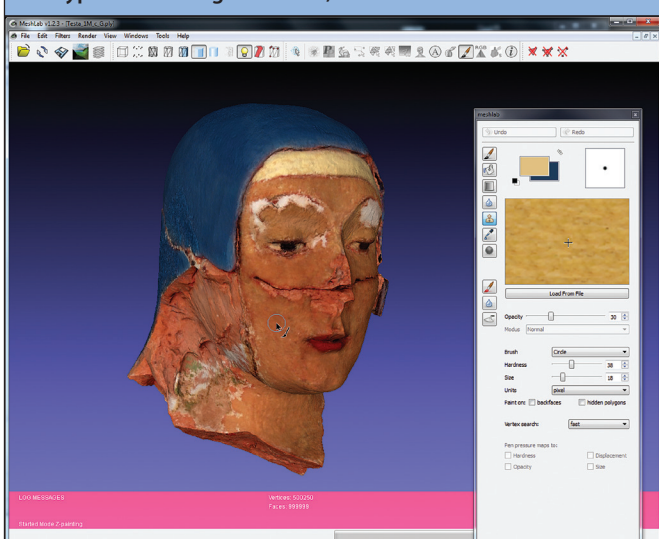

Figure 9. MeshLab repainting session, with an intermediate result over the Pietranico Madonna.

are improving scholars' capabilities to analyze, compare, build, and assess their hypotheses.

The two main issues in making this ideal goal a concrete result are

- the further improvement of the tools oriented to the specific needs of CH practitioners, and
- the consolidation of a multidisciplinary background knowledge.

Future research efforts will require more flexible and easier-to-deploy methodologies for the high-quality sampling of surface reflection properties. Sampling the surface reflection is important for rendering and for characterizing the material composition and conservation status of surfaces. Another topic for future research is improved modeling methodologies for the simulation of surface or material deterioration that encompass both shape and color changes. A near-term goal might be the implementation of a "digital time machine" that could project an artwork's future condition, subject to corrosion or deterioration, such as the erosion of sculpted stone decorations from pollution. The same system might also project from an artwork's present state into the past by producing hypotheses about its original shape, essentially inverting the effect of deterioration.

The development of ready-to-use CH tools is not only a matter of increased research effort. It will require the interest of major companies, since thus far the small economic value of CH-related applications has not attracted them, making technological advances slow. Yet there is hope because, while research, conservation, and restoration are small markets, the wider market, which encompasses multimedia installations for museums or didactic resources for electronic learning, is larger. Technologies for that market, either focusing on data acquisition or tools development, will have application to CH research or conservation.

The second issue concerns the need for a multidisciplinary background, because development should not be technology-driven, a common error that technologists make. Rather, such development should focus on the real needs of CH practitioners. At the same time, these practitioners should become proficient in using new digital technology. When they perceive knowing how to manage technology to be as important as knowing an ancient language, it will transform the way archaeologists preserve, record, and restore the world's rich cultural history. **C**

Acknowledgments

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Roberto Scopigno is a research director at the Institute of Information Sciences and Technologies (ISTI) of the Consiglio Nazionale delle Ricerche (CNR, Italian National Research Council) and leads the Visual Computing Lab. His research interests include 3D scanning, surface reconstruction, multiresolution, scientific visualization, and cultural heritage. Contact him at roberto.scopigno@isti.cnr.it.

Marco Callieri is a researcher at ISTI-CNR. His research interests include 3D scanning, color and appearance acquisition, large 3D dataset manipulation, and rendering, focusing on the use of 3D digital technologies in cultural heritage. Callieri received a PhD in computer science from the University of Pisa. Contact him at m.callieri@isti.cnr.it.

Paolo Cignoni is a senior research scientist at ISTI-CNR. His research interests focus on computer graphics, ranging from level-of-detail and out-of-core techniques for visualization and processing of huge 3D datasets to 3D scanning data processing, with a particular focus on its use in cultural heritage and scientific visualization (molecular visualization and isosurface extraction). Cignoni received a PhD in computer science from the University of Pisa. Contact him at p.cignoni@isti.cnr.it.

Massimiliano Corsini is a researcher at ISTI-CNR His research interests include computer graphics, computer vision, and image processing, focusing on 3D watermarking, perceptual metrics, visual appearance acquisition and modeling, and image-based relighting. Corsini received a PhD in information and telecommunication engineering from the University of Florence. Contact him at m.corsini@isti.cnr.it.

Matteo Dellepiane is a researcher at ISTI-CNR. His research interests include 3D scanning, digital archaeology, color acquisition and visualization on 3D models, and perceptual rendering. Dellepiane received a PhD in information engineering from the University of Pisa. Contact him at m.dellepiane@isti.cnr.it.

Federico Ponchio is a research scientist at ISTI-CNR. His research interests include multiresolution representations, interactive visualization, geometric processing, and Web applications. Ponchio received a PhD in computer graphics from the University of Claustal, Germany. Contact him at f.ponchio@isti.cnr.it.

Guido Ranzuglia is a researcher at ISTI-CNR. He has been involved in several CNR-ISTI projects and is the core developer of MeshLab. Ranzuglia received an advanced degree in computer science (Laurea) from the University of Pisa. Contact him at g. ranzuglia@isti.cnr.it.

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