Using optically scanned 3D data in the restoration of Michelangelo's David

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ABSTRACT

Modern 3D scanning technologies allow to reconstruct 3D digital representations of Cultural Heritage artifacts in a semi-automatic way, characterized by very high accuracy and wealth of details. The availability of an accurate digital representation opens several possibilities of utilization to experts (restorers, archivists, museum curators), or to ordinary people (students, museum visitors). 3D scanned data are commonly used for the production of animations, interactive visualizations, or virtual reality applications. A much more exciting opportunity is to use these data in the restoration of Cultural Heritage artworks. The integration between 3D graphic and restoration represents an open research field where many new supporting tools are required; the David restoration project has given several starting points and guidelines to the definition and development of innovative solutions.

Digital 3D models can be used in two different but not subsidiary modes: as an instrument for the execution of *specific investigations* and as a *supporting media* for the archival and integration of all the restoration-related information, gathered with the different studies and analysis performed on the artwork.

In this paper we present some recent work done in the framework of the Michelangelo's David restoration project. A 3D model of the David was reconstructed by the Digital Michelangelo Project, using laser-based 3D scanning technology. We have developed some tools to make those data accessible and useful in the restoration. Preliminary results are reported here together with some directions for further research.

Keywords: 3D scanning, laser scanners, digital 3D models, restoration, scientific visualization

1. INTRODUCTION

Modern 3D scanning technologies (in general, based on optical devices) allow to reconstruct 3D digital representations of real objects in a semi-automatic way, with high precision and wealth of details.[1,2] This technology has been often applied to the Cultural Heritage (CH) field, since CH requirements (high accuracy and dense sampling, joint management of shape and optical properties of the surface) fit well with the 3D scanning potentialities. Pioneering activities started in US and Canada[3–6] and many of these efforts focused on Italian artistic masterpieces. 3D scanning is in general performed using active optical technology,[2] based either on laser or incoherent structured light. In both cases, most of the instruments available ensure very high accuracy (in the order of 0.1 mm or better). Some instruments allow also the acquisition of the color detail.

An accurate digital model of Michelangelo's David has been created during the Digital Michelangelo project (1999-2001), coordinated by Professor Marc Levoy from Stanford University.[5] The Digital Michelangelo project had a very broad goal: to scan a large number of the Michelangelo's sculpture masterpieces and at the same time to improve scanning technologies. The David model was reconstructed using a custom Cyberware laser scanner, coupled with a computer-controlled gantry which allowed to the Stanford operators to orient (pan and tilt) and to move vertically the scanner in a remote manner; the large set of range maps acquired (around 4000 just for the David model) was post-processed using the set of tools developed by the Stanford's Computer Graphics Lab. The final model released so far is composed by 56 million faces, and has been reconstructed from the range maps using a reconstruction grid with 1 mm. cell size. Acquisition and reconstruction required a long time because of dimensions and complexity of the statue and also due to the pioneering status of the technology. To make those data more easily manageable, we applied our simplification technology[7] to reduce the data complexity to the size and accuracy needed by each different use or application.

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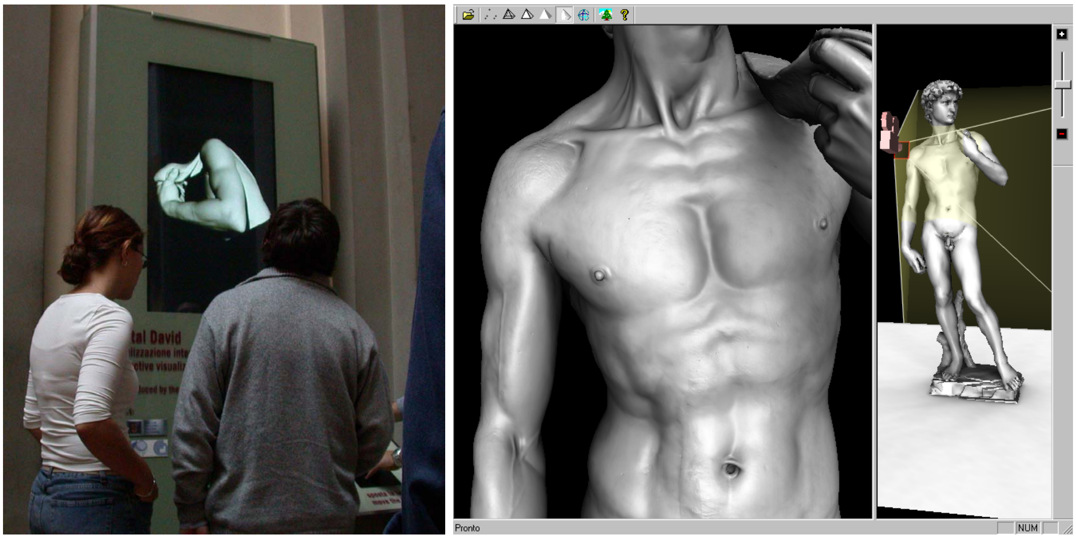

Figure 1. Two different visualization systems of 3D digital model: on the left, the stand (kiosk) created by Stanford University and CNR and recently installed in the Museum Gallerie dell'Accademia; on the right, the Inspector's virtual navigation system, developed by CNR.[9]

The availability of an accurate digital representation opens several possibilities of utilization to the experts (restorers, archivists, museum curators) or to ordinary people (students, museum visitors). Today most of the results of the scanning projects run so far have been used just to produce still images or [interactive] animations for *didactic* applications, *multimedia presentation* or *virtual reality* navigation: the classical rendering-oriented applications are still predominant[8, 9] (see some examples in Fig. 1). On the other hand, people working in the CH field are initially fascinated by the beautiful images we can produce, but quite fast they ask for tools really useful in their day by day work. We agree that the use of 3D models should go beyond the simple possibility to create synthetic images.

The availability of a complete and accurate knowledge of the shape's characteristics of CH artworks is needed to catalogue and well preserve the good, or to produce copies without the necessity to cast a mould. This can entail both to store digital 3D model in national/museum catalogues (replacing 2D photographs which are today the standard representation media), or to reconstruct physical replicas of the work of art from the digital model. Semi-automatic technologies of reproduction can be employed to produce copies on noble materials (e.g. stone), and it is important to underline how simple is to choose different scales of reproduction from the digital 3D model.

An exciting opportunity is to make an intense use of digital 3D models in artworks *restoration*. The integration between 3D graphic and restoration represents an open research field and the David restoration project has given several starting points and guidelines to the definition and development of innovative solutions. Our activity is based on problems and specific requests suggested by restorers and briefly described in the following sections. A 3D digital model can be used to support restoration in two different but not subsidiary modes: as a *instrument* or tool for the execution of specific *investigations*, or as a *supporting media* for the archival and integration of the multimedia data produced by the different scientific studies. The David restoration qualifies as an ideal testbed, since a complex set of scientific investigations has been planned both before and after the restoration intervention. This gave us the opportunity of attempting different methodologies to support the restorers and scientist work with either the 3D model or the synthetic images produced from the digital model. Let us describe in the following two sections the work done.

2. 3D DATA AS A TOOL TO STUDY AN ARTWORK

As we introduced before, the availability of a digital 3D model can support the execution of specific *investigations* using just a digital approach. Two main "digital" investigations were performed in the restoration of the David: the characterization of the *surface exposure* to the fall of contaminants, and the computation of a number of *physical measures*.

2.1. Surface exposure characterization

We designed and implemented a tool to evaluate the *fall of contaminants* (e.g. fall of rain, mist or dust) on the David's surface; this phenomena depends on: the direction of fall of the contaminant, the surface slope, the self occlusion and accessibility of different surface parcels. Using this tool on the digital model of a statue (or of a building) allows to come to several qualitative and quantitative results, useful to characterize the artwork surface. The falling directions of the contaminant agents is modelled by assuming a *random fall direction*, uniformly distributed around the vertical axis of the statue within an angle α which defines the maximum fall inclination. Given a falling distribution d_i, and a point p_j of the surface of the model, we compute if p_j can be directly view along direction d_i, or in other words, if we can reach p_j coming from direction d_i without hitting the rest of the surface. This computation is repeated for each vertex of the surface and for a set of 1024 random direction sampled according the above distribution; for sake of efficiency we exploit graphics hardware to compute if a given vertex can be directly view along a direction. At the end of this process we have for each vertex an exposure value that corresponds to the number of direction from which it is visible, or in other words to an estimation of the solid angle form which this point can be reached with respect to a given cone of directions.

Figure 2 shows some results obtained on the David (using an α value equal to 5 degrees on the left, and 15 degrees on the right); the different exposures are visualized using a false-color ramp, with red=absence of fall and blue=high density of fall*. The digital 3D model is therefore used both to compute the simulation and to present the results obtained in a visual manner. Numeric data can also be returned (tables and graphs).

2.2. Physical measures

Physical measures can be computed directly on the digital 3D model. Some of those are the *surface* of the artwork (19.47 squared meters in the case of the David) or its *volume* (2.098 cubic meters). Known the unit weight of the constituent material of the artwork (e.g. marble weight per $dm.^3$), the total *weight* can be immediately computed from the volume measure.

Point-to-point distances are also often needed, and can be simply computed on the 3D model by adding a *linear measuring* feature to the browser used to visualize the digital model. A linear measuring feature has been included in our visualization tool (Easy3DView): user simply selects any pair of surface points, and the tool computes the linear distance between those two points.

One of the issues under evaluation in the David restoration is the static conditions of the statue. At the end of the nineteen century the David was moved from outdoor to a museum, and this decision was also due to the cracks on the back of the ankles which frightened the curators. These cracks could have been generated by a wrong distribution of the mass of the statue (there are some historical papers which sustain that the original basement was not properly planar, and the statue was slanting forward). Therefore, an investigation on the static conditions of the statue was included in the set of investigations to be done before the restoration. Basic data for the evaluation of the static conditions of the artwork are: the location of the *barycenter* of the statue, the vertical *falling line* of the barycenter, the volume and mass. These data were computed directly on the digital 3D model, after performing various necessary preprocessing steps on the original 3D data. The first step was to register the orientation of the model in order to match with the real one: the models distributed by the Digital Michelangelo Project are not perfectly vertical so we checked the real orientation of the David's basement and rotated the digital model in order to match with the real vertical position. The second step was to produce a *usable* digital model: computing mass properties requires that the digital model is a closed, water-tight 2-manifold surface. For this purpose we have used the algorithm presented in[10] to remove all open holes in the digital surface and

*Please note that most of the figures in this paper contain color, and readability is insufficient if printed B/W. A pdf copy of this paper is available on our web, at: http://vcg.isti.cnr.it/publications/publications.htm

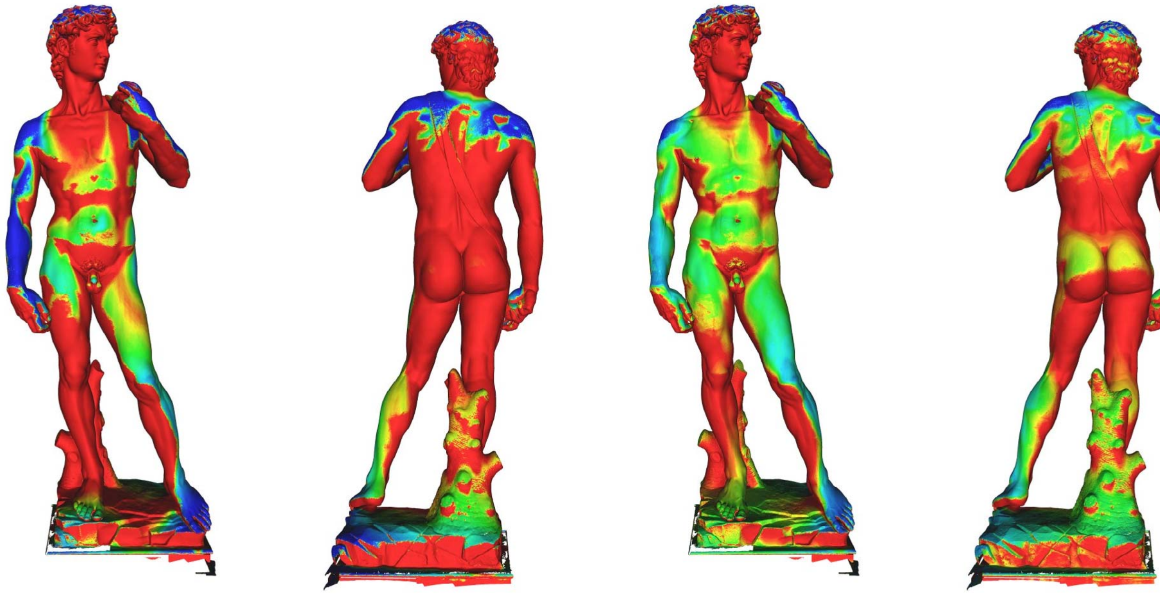

Figure 2. Exposure of David'surface to dust or other contaminators. This visualization shows, using a false-color ramp, the different classes of exposition produced by the simulation (red: absence of fall, blue: high density of fall), under a maximal angle of fall of 5 degrees (on the left) and 15 degrees (on the right).

to build a watertight model; these holes were associated to many small surface sections not sampled by the 3D scanner. Given the high memory and computing requirement of this technique we have chosen to reconstruct a smaller model of around one million faces. Fortunately the approximation introduced by this simplification step does not affect in a significant way the final computation of the mass properties. The approximation error that we introduce using a simplified model in the computation is not biased and has a near-to-zero average (with respect to the original surface), therefore, during the integration process required to compute mass properties, it is almost entirely summed away. We have empirically proved this property by reconstructing models with even lower accuracy (500k and 100k faces) and finding that the computed barycenter positions are not significantly affected by the change of resolution.

The mass properties (volume, center of mass and the moments and products of inertia of the center of mass) of the polyhedral digital model have been computed using an algorithm that exploits an integration of the whole volume assuming constant density of the mass.[11] The algorithm is designed to minimize the numerical errors that can result from poorly conditioned alignment of polyhedral faces. All required volume integrals of a polyhedron are computed together during a single walk over the boundary of the polyhedron.

From this computation we obtained that the statue's barycenter is placed in the interior of the groin, approximately in the pelvis (see Fig. 3). The vertical projection of the barycenter on the base of the statue (i.e. the sculptured rocky base where the David stands) is the blue line which exits from the marble on the high posterior part of the left thigh and enters again in the marble on the right foot. The projection of the barycenter vertical line on the statue base has been documented with a large size plot (see Fig. 4) produced with a proprietary application called *Cavalieri*.[12] We designed Cavalieri to give to restorers a tool to produce easily large format prints from the very high resolution 3D models produced with 3D scanning technology. Currently, existing commercial drafting systems do not allow to manage triangulated 3D surfaces composed by many million faces. Cavalieri supports easy specification of orthographic drawings and cut-through sections, which are given in output as very high resolution images (whose size is in accord with the user-selected reproduction scale and printer resolution).

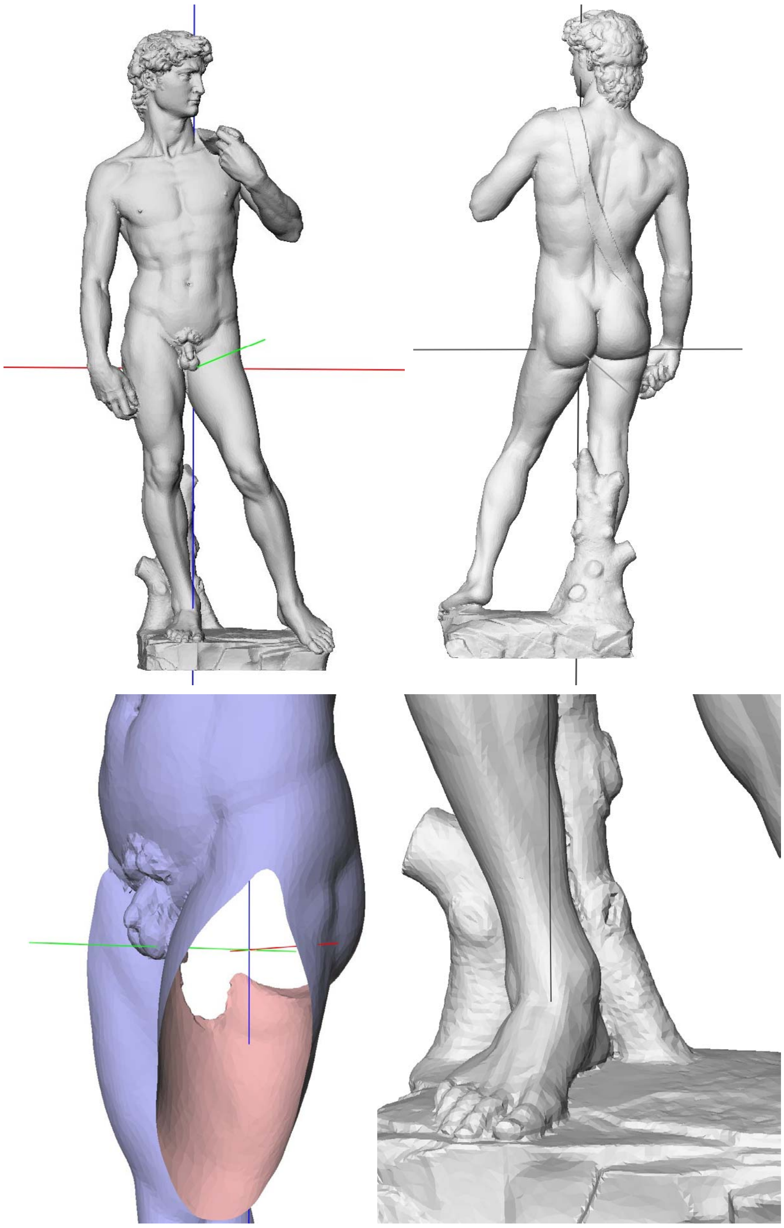

Figure 3. Calculation of the spatial position of David's barycentre and its vertical projection line (in blue).

3. 3D MODELS AS A MEDIA TO INDEX, ARCHIVE AND PRESENT RESTORATION INFORMATION

A second important use of 3D models is to consider them as an instrument to document, organize and present the restoration data. During the David restoration campaign, a number of *scientific investigations* have been performed; some of them will be repeated with the passing of time, in order to monitor the status of the statue. These investigations include: different chemical analysis (to find evidence of organic and inorganic substances present on the surface of the statue), stone characterization, UV imaging, precise colorimetric characterization of the marble, etc.

All the results produced by the scientific investigation will be organized and made accessible through a system

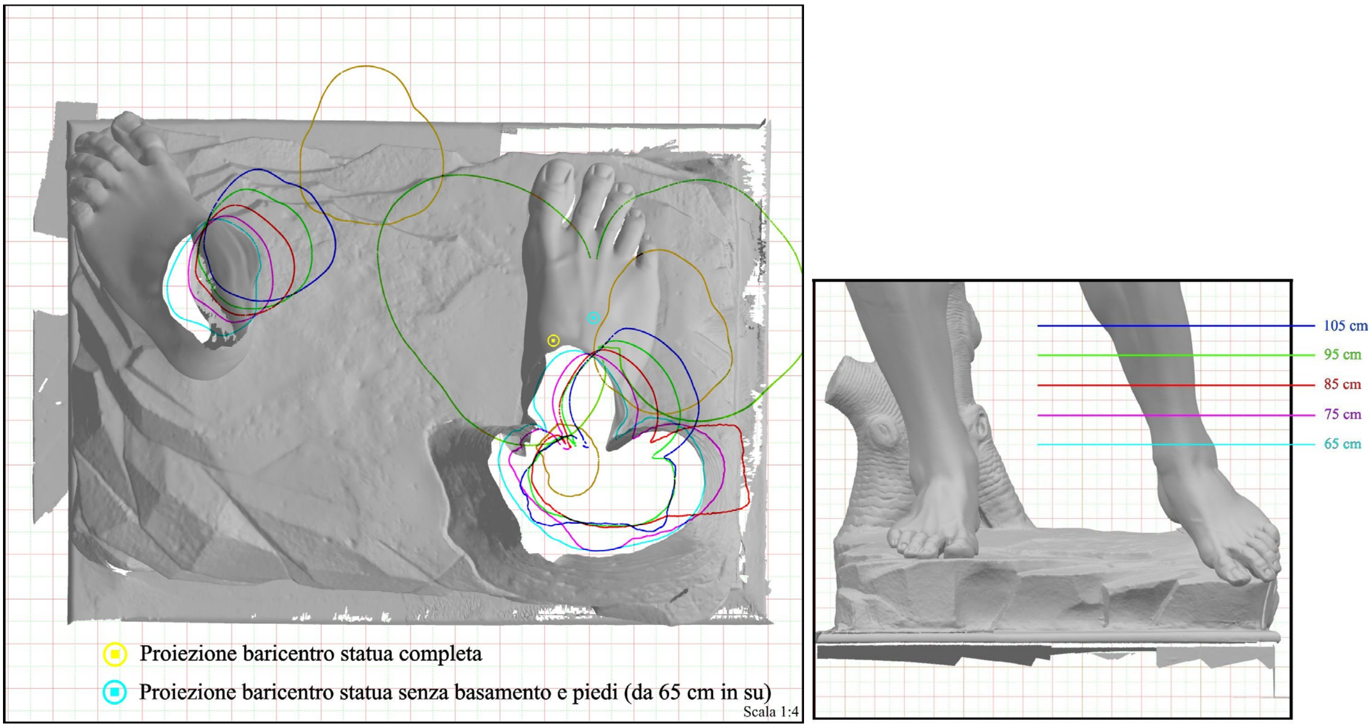

Figure 4. Visualization of the barycenter projection line (marked by a yellow circle) and of the profiles of some cut-trough sections (ankles, knees and groin; see the respective hight in the right-most image).

implemented with web technology, easy to consult and compare. The 3D model of the David will be used to build a spatial index to those data (see Fig. 5), pointing out their location on the surface of the statue and supporting hyperlinks to web pages describing in detail the corresponding investigation and the results obtained.

Moreover, some investigations produced image-based results, which can be directly mapped on the statue surface and presented in an integrated manner. As an example, this is the case of the UV imaging investigation; these images are produced under ultra-violet lighting and they are very important to give visual evidence to the presence of organic material on the marble surface (e.g. wax, which has to be removed with a proper solvent). The UV investigation performed by the colleagues of the *Opificio delle Pietre Dure* (a restoration laboratory in Florence) produced since now 11 images, which can be mapped onto the 3D surface using an approach which computes the inverse projection (camera specification) from each single photograph and combines all the available photographs in a single texture map which is mapped on the 3D geometry.[13, 14] This process allows to inspect all of the images at the same time and to map the 2D information on the corresponding location of the 3D object surface (Fig. 6).

Another important source of data is the high-resolution photographic survey of the David, performed by a professional photographer according to the specifications given by our group. The photographic sampling was planned as shown in Fig. 7. The reason for planning those photos is to document the status of the statue before the restoration. Standard RGB images can be mapped to the 3D mesh (see Fig. 8) with the same methodology used for the UV images.[13, 14]

Moreover, a restorer (Agnese Parronchi) has performed a precise graphic survey on the status of the David's surface. She drew very accurate annotations on those high resolution photos, covering all the surface of the David. These annotations describe in a very detailed manner the presence of: (1) imperfections in the marble (small holes or veins); (2) deposits and strains (e.g. brown spots or the traces of straining rain); (3) surface consumption; and (4) traces of the Michelangelo's workmanship. These annotations have been drawn by Parronchi on transparent acetate layers positioned onto printed images. Therefore, we have 4 different graphic layers for each one of the

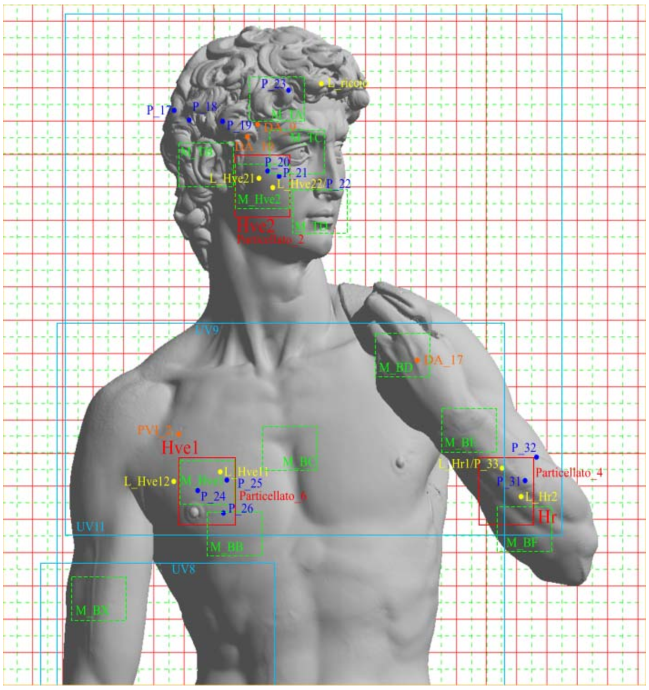

Figure 5. Scientific investigations were performed on selected points or areas on the statue's surface; these location are mapped onto the digital model.

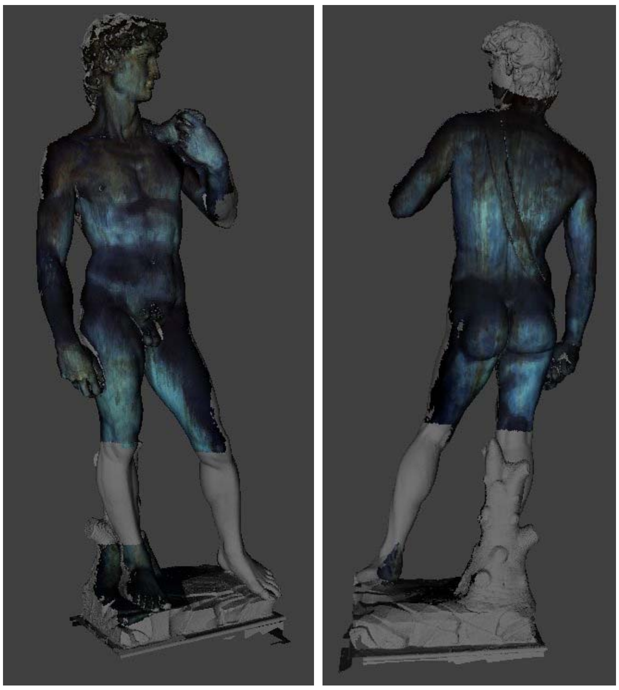

Figure 6. Mapping of the UV images on the respective section of the statue's digital model.

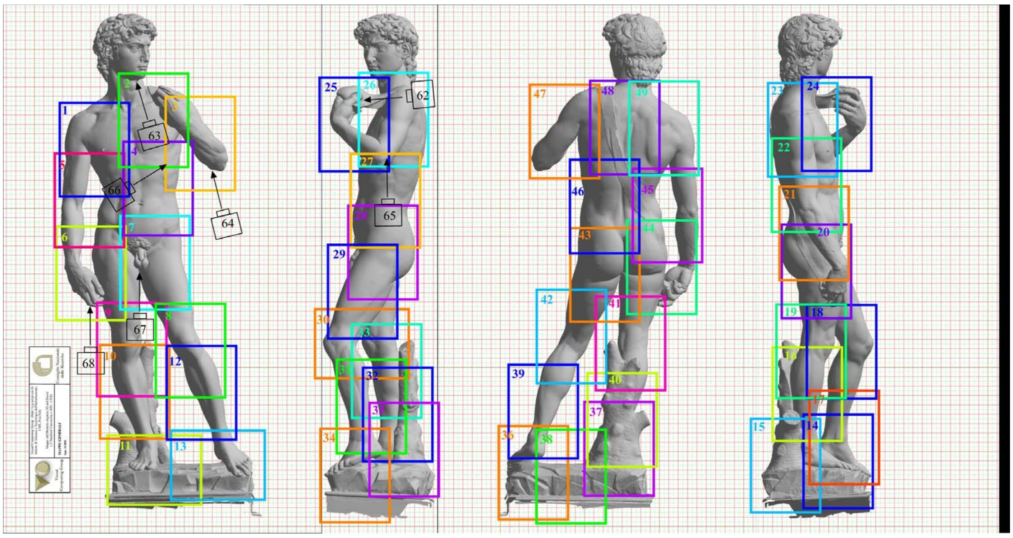

Figure 7. Schema of the photographic campaign, which divides the David surface in 68 photo shots (the head is covered by other images not shown in this schema).

Figure 8. Mapping of a RGB images on a section of the statue's digital model (images rendered from the 3D model).

68 high-resolution photos. These graphic relief have been scanned, registered (rototranslation+scaling) on the corresponding RGB image, and saved at the same resolution of the corresponding RGB image. A web based system is in advanced implementation state; it allows to browse the RGB images and to plot in overlay any selected relief layer. We decided to show the reliefs overlayed on the 2D RGB images, thus to use a 2D-based visualization approach, instead than trying to map reliefs and RGB images on the 3D surface. This choice was justified by the large amount of information contained in those images and reliefs (5M pixels each), which makes very hard to map and render them in interactive time onto a 3D surface. In this case the 2D space is much more adequate for mapping the info, since the access to those data will be selective (just a small region of surface visible).

4. CONCLUDING REMARKS

We have presented some examples of how we have used a 3D digital model in the framework of a restoration project. As we have shown, the 3D representation has been used both to execute some particular investigations and as a supporting media for the archival and integration of the restoration-related information. The adoption of a similar approach in a standard restoration project is affordable, since the cost for acquiring a 3D model of an artwork is progressively reducing. While the budget of early scanning project was rather high, scanning an artwork with state-of-the-art HW and SW technology requires an effort which can be estimated in a few days. As an example, we recently performed a complete scanning of the Minerva of Arezzo[15] (a bronze statue, 1.60 m. tall) in just one week[†], including in this time also the range-maps post-processing.

Therefore, the main difficulty encountered is not related to the scanning phase, but to the lack of tools oriented to restoration or, more in general, which could help in the proficient use of 3D graphics in the CH domain. A clear example is the use of 3D graphics to present other data: the tool needed would be very similar to what do we have in the case of geographic data management. In most cases, we need some sort of GIS-like tool which should allow us to easily map data to a standard 3D geometry, or to segment a surface according to some sort of categorization of the same surface. Unfortunately, the CH domain is still a nice market and does not attract the interest of software companies. Doing research in this domain means that we are often requested to design and implement tools which could have been done by a professional software developer (see for example the Cavalieri system[12]), and this makes the work of a CG-oriented researcher harder.

Another critical point is the acceptance of digital methodologies by CH people. They usually have a non-technical education and are often very sceptical and reluctant to endorse digital methodologies. Fortunately, our experience is that this initial negative position can be easily transformed when we are able to offer them not just nice images, but tools really usable in their daily work.

ACKNOWLEDGMENTS

We would like to thank dr. Franca Falletti and dr. Mauro Matteini (chairs of the David restoration project) and all the colleagues involved in the David restoration project for the many stimulating and fruitful discussions. We acknowledge the financial support of the EU IST-2001-32641 "ViHAP3D" project.

REFERENCES

1. F. Bernardini and H. E. Rushmeier, "The 3D Model Acquisition Pipeline," *Computer Graphics Forum* **21**, pp. 149–172, March 2002.
2. F. Chen, G. Brown, and M. Song, "Overview of three-dimensional shape measurement using optical methods," *Optical Engineering* **39**, pp. 10–22, January 2000.
3. M. Soucy, G. Godin, R. Baribeau, F. Blais, and M. Rioux, "Sensors and algorithms for the construction of digital 3d colour models of real objects," in *Proceedings IEEE Intl. Conf. on Image Processing*, pp. 409–412, (Lausanne, Suisse), September 16-19 1996.

[†]See some data on our last Minerva scanning times by following the Digital Minerva link on http://vcg.isti.cnr.it/projects/projects.htm

4. H. Rushmeier, F. Bernardini, J. Mittleman, and G. Taubin, “Acquiring input for rendering at appropriate levels of detail: digitizing a Pietá,” in *Rendering Techniques '98*, G. Drettakis and N. Max, eds., pp. 81–92, Springer Wien, 1998.
5. M. Levoy, K. Pulli, B. Curless, S. Rusinkiewicz, D. Koller, L. Pereira, M. Ginzton, S. Anderson, J. Davis, J. Ginsberg, J. Shade, and D. Fulk, “The Digital Michelangelo Project: 3D scanning of large statues,” in *SIGGRAPH 2000, Computer Graphics Proceedings*, *Annual Conference Series*, pp. 131–144, Addison Wesley, July 24-28 2000.
6. G. Tucci, F. Costantino, G. Guidi, M. Pieraccini, D. Ostuni, and J. Beraldin, “Photogrammetry and 3D scanning: Assessment of metric accuracy for the digital model of Donatello's Maddalena,” in *Workshop on 3D Digital Imaging and Modeling*, pp. 20–28, (Padova, Italy), April 3-4 2001.
7. P. Cignoni, C. Montani, C. Rocchini, and R. Scopigno, “External memory management and simplification of huge meshes,” *IEEE Transactions on Visualization and Computer Graphics* **9**, p. (in press), 2003.
8. S. Rusinkiewicz and M. Levoy, “QSplat: A multiresolution point rendering system for large meshes,” in *Comp. Graph. Proc., Annual Conf. Series (SIGGRAPH 00)*, pp. 343–352, ACM Press, July 24-28 2000.
9. R. Borgo, P. Cignoni, and R. Scopigno, “An easy to use visualization system for huge cultural heritage meshes,” in *VAST 2001 Conference Proc.*, D. Arnold, A. Chalmers, and D. Fellner, eds., pp. 121–130, ACM Siggraph, (Athens, Greece), Nov. 28-30 2001.
10. J. Davis, S. Marshner, M. Garr, and M. Levoy, “Filling holes in complex surfaces using volumetric diffusion,” in *First Int. Symp. on 3D Data Processing, Visualization and Transmission (3DPVT'02)*, pp. 428–438, IEEE Comp. Soc., 2002.
11. B. Mirtich, “Fast and accurate computation of polyhedral mass properties,” *Journal of Graphics Tools* **1**(2), pp. 31–50, 1996.
12. M. Callieri, P. Cignoni, R. Scopigno, G. Gori, and M. Risaliti, “Beyond manual drafting: a restoration-oriented system,” Tech. Rep. TR-03, I.S.T.I. – C.N.R., Pisa, Italy (submitted paper), June 2003.
13. C. Rocchini, P. Cignoni, C. Montani, and R. Scopigno, “Acquiring, stitching and blending diffuse appearance attributes on 3d models,” *The Visual Computer* **18**(3), pp. 186–204, 2002.
14. M. Callieri, P. Cignoni, and R. Scopigno, “Reconstructing textured meshes from multiple range rgb maps,” in *7th Int.l Fall Workshop on Vision, Modeling, and Visualization 2002*, pp. 419–426, IOS Press, (Erlangen (D)), Nov. 20 - 22 2002.
15. C. Rocchini, P. Cignoni, C. Montani, P. Pingi, R. Scopigno, R. Fontana, L. Pezzati, M. Cygielman, R. Giachetti, and G. Gori, “3D scanning the Minerva of Arezzo,” in *ICHIM'2001 Conf. Proc., Vol.2*, pp. 265–272, Politecnico di Milano, 2001.