Restoring *David* using 3D

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Begun in Florence, Italy, in 2002, our participation in refurbishing Michaelangelo's *David* has produced several useful restoration guidelines. These guidelines can help restorers select the proper procedures for the task and, objectively, assess the results. The work also has helped us develop innovative ways to process and visualize 3D data in cultural heritage projects.

The *David* restoration was an ideal test bed. The restoration project leaders had planned a complex set of scientific investigations before and after the restoration intervention. Thus, we could try various methodologies to support restorers and scientists with visualization tools based on 3D digital models. For instance, 3D digital models can be a tool for undertaking specific investigations, or as supporting media for archiving and integrating the restoration-related information. (Data that was gathered with the different studies and analyses performed on the artwork.)

Cultural restoration opportunities

Until now, in cultural heritage restoration, 3D models have been used primarily for still and interactive rendering and for physical reproduction via rapid prototyping technology. However, this field offers many other opportunities for using accurate 3D models and visualization. A complex set of investigations usually precedes a valuable artwork's restoration, including visual inspection, chemical analysis, image-based analyses (RGB or colorimetric, ultraviolet light reflection and x-ray among others), structural analysis and archival search. What's more, these analyses might need to be repeated from time to time while monitoring the artwork's status and the restoration's progress. 3D modeling can be of great assistance in many of these instances.

Questions arise about how best to manage the resulting multimedia data—such as text, annotations, historical documents, 2D and 3D images, vector reliefs and numeric data coming from the analysis—in an integrated framework. How do we make all the information accessible to the restoration staff and, possibly, to other experts and the general public?

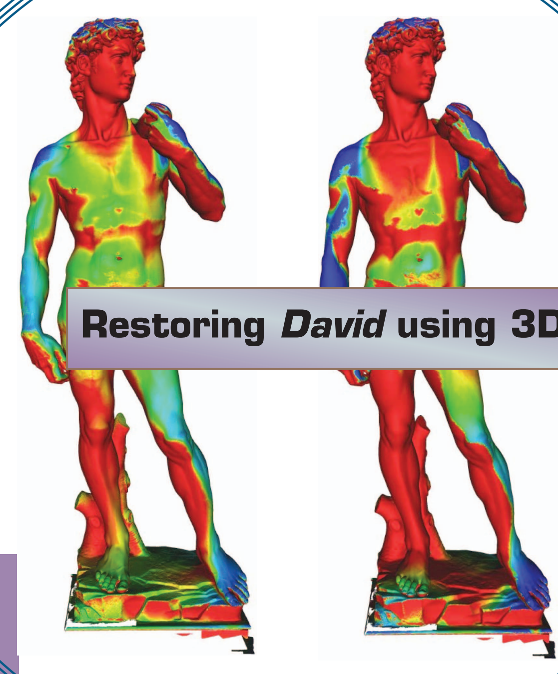

Fig. 1 Exposure of David's surface to dust or other contaminations. This visualization uses a false-color ramp to show classes of exposition produced by the simulation (red: absence of fall, blue: high density of fall), under a maximal angle of fall of (a) 5 degrees and (b) 15 degrees.

The information, for the most part, relates to various spatial locations on the artwork's surface. Therefore, 3D models can be a valuable way to index, store, cross correlate and visualize this information. (The easiest way to present data is to directly map it onto the corresponding surface point/region with tools provided for selective visualization. With the data integrated according to their spatial distribution, humans have an easier time analyzing it. 3D models can also provide a valuable instrument in the final assessment of the work done. They can support and verify the interactive inspection of the multiple digital models (corresponding to pre- and post restoration status) when checking for possible shape and color variations.

This was not the case with the *David*, whose restoration was mostly a very delicate cleaning. However, some restoration actions do modify quite dramatically either the shape or the color of the artwork. Interactive visualization tools can support documentation in a compelling and accurate manner as well as provide access to the general public.

We tested different uses of 3D graphics in the *David* restoration, ranging from classical scientific visualization tasks to more complex information visualization applications. Our experience indicated that available tools—either commercial or academic systems—do not satisfy all the potential needs of computer-aided restoration. Computer-aided restoration is still a new domain and very small in terms of economic value. Most of the tools used came from other application domains (such as medical visualization, CAD and engineering).

As an example, standard visualization features are sufficient for some cases, e.g. when we need to present a scalar field mapped over a 3D surface (see Fig. 1). There are many other potential tasks that require more sophisticated tools, such as the simulation of the surface degradation, the virtual restoration (i.e. inverting the effects of degradation), the virtual and possibly automatic recombination of fragmented objects.

Moreover, images presented on a display cannot be the only communication channel. While an impressive amount of information can be encoded in images, the Heritage field has specific requirements concerning the way "images" are produced and presented. For instance, cultural heritage investigators often still require paper-based documents (see "3D graphics & cultural heritage" sidebar). Therefore, visualization instruments should be able to encode information into printable documents. Basic feature requirements are 1) the accuracy of the printed representation—display resolution is typically poor when printed on a large paper format—and 2) the capability to easily produce output in any scale factor selected by the user.

In the *David* restoration, we performed two main digital investigations: characterizing the surface exposure with respect to the fall of contaminants and computing a number of physical measures. In both cases, we implemented original algorithms to process data and present the results to the users.

Surface exposure characterization

We designed and implemented a tool to evaluate the exposure of the *David's* surface to falling contaminants, such as rain, mist or dust. This evaluation gives to the restorers some hints on which surface regions are more delicate, thus, possibly the most affected by the marble degradation process.

This exposure depends on the direction of the contaminant's drop, and the slope of and access to the different sections of the statue's surface. The tool models the falling directions of the contaminant agents by assuming a random fall direction, uniformly distributed around the statue's vertical axis within a maximum angle of inclination a.

Figure 1 shows some results obtained on the *David* restoration. The different exposures are visualized using a false-color ramp. The same digital 3D model tool computes the simulation and presents the results visually. The tool also produces numeric data in tables and graphs. Restorers verified the results presented with their visual analysis of the statue's marble conditions.

Physical measures

We could compute physical measures directly on the digital 3D model, either using *David's* surface (19.47 square meters) or volume (2.098 cubic meters). If we know an artwork material's unit weight, we can immediately compute the total weight. To determine point-to-point distances, we can add a linear measuring feature to the browser. Our visualization tool, *Easy3Dview*, includes a linear measuring feature. Users select two points on *David's* surface and the tool computes the linear distance between them.

The cracks on the back of the *David's* ankles concerned the curators. Erroneous distribution of the statue's mass might have generated these cracks. Historical papers suggest that the original basement was not properly planar, thus, making the statue slant forward. So before the restoration work began, we investigated the statue's *statics*—that is, forces that produce equilibrium among material bodies.

The basic data needed for the static investigation are the mass properties—volume, center of mass, and the moments and products of the center of mass's inertia. We computed these properties directly onto the digital 3D model using an algorithm that exploits an integration of the whole volume, assuming constant density of mass. The computation showed that the statue's center of mass is located in the interior of the groin, approximately at the pelvis (see Fig. 2a). The center of mass's vertical projection on the statue's base—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 reenters the marble on the right foot on the left side of Figure 2a. We also estimated the center of mass by removing the basement (cutting the statue at the height of the main cracks); the right side of Fig. 2a shows the new position.

We used Cavalieri, a proprietary application, to project the statue base's center of mass onto a large size plot shown in Fig. 3a. We designed Cavalieri to support the easy production of large-format prints—orthographic drawings and cut-through sections produced based on the user-selected reproduction scale—from the very high-resolution 3D models produced with 3D scanning technology. The restorers and the experts working with the scientific analysis have used the prints produced extensively; they found the 3D renderings much more helpful than printed photographs, given the great flexibility in selecting any view and the zooming factor.

Using 3D models with data

During the *David* restoration campaign, the restorers performed a number of scientific investigations that monitored the statue's status. These investigations included: chemical analyses to find evidence of organic and inorganic substances present on the statue's surface; petrographic and colorimetric characterization of the marble; UV imaging and x-ray imaging. The *David* Restoration Project is organizing these scientific results and will make them available through an electronic media, an interactive DVD that will be produced and dis-

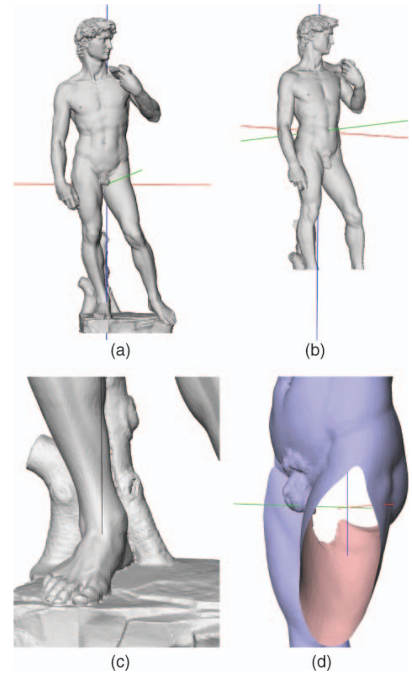

Fig. 2 Spatial location of David's barycenter (a) with and without basement and feet; (b) zoomed images.

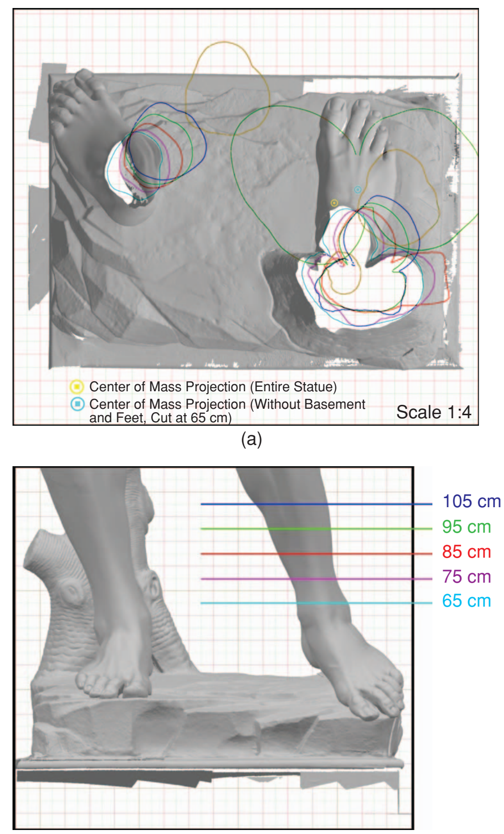

Fig. 3 (a) Visualization of the center of mass's projection (marked by a yellow circle) and (b) profiles of some cut-trough sections (ankles, knees and groin; see the respective height in the right-most image).

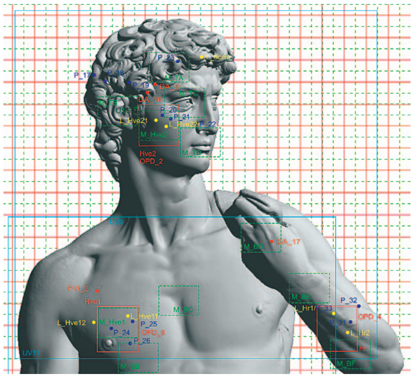

Fig. 4 The digital model serves as an index to the scientific investigations performed on selected points or subregions of the statue's surface.

Fig. 5 Mapping multiple UV images on the digital 3D model.

tributed in 2005. The 3D model of the *David* will serve to build spatial indexes to those data (see Fig. 4), indicating their location on the surface and supporting hyperlinks to the project's Web pages.

Some investigations produced image-based results that can be directly mapped on the statue's surface and presented in an integrated manner. For example, images produced under UV lighting in the UV imaging investigation gave visual evidence of organic deposits—wax, in this case—that will need to be removed. The UV investigation performed by the *Opificio delle Pietre Dure*, a renowned Italian public restoration institution, produced many 2D images taken from different viewpoints. We then mapped these images onto the 3D surface.

We started by computing the inverse projection and the camera specification from each single photograph. We then combined all the available photographs into a single texture map wrapped around the 3D geometry. Using these visualization processes, we plotted the image-based information onto the corresponding location of the 3D object surface. We then inspected all of the images simultaneously using an interactive browser (see Fig. 5).

The high-resolution photographic survey of *David*, performed by a professional photographer with digital technology following specifications given by our group, was another important source of data. Figure 6 shows the photographic sampling plan. It served to document the statue's status before the restoration began.

These RGB images also can be mapped to a 3D mesh (see Fig. 7) with the same methodology used for the UV images. Moreover, the restorers performed a precise graphic survey of the status of *David's* surface. She drew accurate annotations on those high-resolution photos, covering the entire surface. These annotations detail imperfections in the marble, such as small holes or veins; the presence of deposits and strains, such as brown spots or rain traces; the surface consumption; and the remaining traces of the Michelangelo's workmanship.

Because the restorers drew these annotations on transparent acetate layers positioned onto each printed photo (in the A3 format), we had four different graphic layers for each of the 68 high-resolution photos. We scanned these graphic reliefs, registered (roto-translation and scaling) them on the corresponding RGB image, and saved them at the same resolution as the corresponding RGB image. We then implemented a Web-based system to browse the RGB images and plot in overlay any user-selected relief layer (see Fig. 8).

Because we show the reliefs as overlays on the RGB images, we used a 2D-based visualization approach, rather than try to map the reliefs and the RGB images on the 3D surface. Given the large amount and complexity of the information contained in those 2D layers (each one is a 5-Mbyte pixel image), mapping and rendering interactively such data on 3D surface is difficult. In this case, the 2D space is a much better choice. This is because access to those data will be selective—the user can browse over small subregions of the *David's* skin. However, again, the 3D model serves as a good spatial index to the set of images.

Conclusions

The 3D representation can serve both to execute particular investigations and to support archiving and integrating the restoration-related information. Costs to acquire a 3D model of an artwork are rapidly falling. Thus, a less well-funded group can take a similar approach for a

3D graphics & cultural heritage

Cultural heritage application requirements—high precision and dense sampling in shape reconstruction, joint management of shape and optical properties of the surface—make 3D scanning a good choice.

Pioneering activities first started in Canada and US with many of these efforts focused on Italian artistic masterpieces. For example, the Stanford's Digital Michelangelo Project performed a major scanning on multiple Michelangelo's statues; among them, a 3D model of the David was reconstructed from 4,000 scanned range maps obtaining a final 3D model encoded by 56 million tiny triangles.

So far, most 3D scanning results have served simply to produce still images, interactive visualizations, or animations, with the classical rendering-oriented applications still being the most predominant. The availability of accurate digital representations of artwork opens up useful possibilities for the experts (e.g. restorers, archivists and museum curators) and for the general public (e.g. students and museum visitors). For instance, while the experts are initially just fascinated by the beauty of the images produced, they soon ask for visualization or data-processing tools to use in their daily work. They are right: The use of 3D models should go beyond the creation of cool-looking synthetic images. However, projects proposing 3D graphics as an analytical tool are still rare.

Combining the use of 3D digital models with ad hoc visualization tools offers exciting possibilities in artwork restoration. We recently performed a complete scanning of the Minerva of Arezzo, a bronze statue measure 1.6 meters tall, in less than one week. However, while acquisition costs for a 3D model of an artwork are falling progressively——the real use of 3D models in the Heritage field is still in its infancy, mainly due to the lack of tools specifically designed for this field.—*MC, PC, FG, GI, CM, PP, FP & RS*

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standard restoration project.

However, the real main difficulty is the lack of visualization tools and metaphors to support the proficient use of 3D graphics in this domain. A clear example is the vast knowledge and data which are associated with an important work of art, and the need to provide computer-based archival and analysis instruments: the graphic 3D tool needed would closely resemble what we have for the organization and processing of geographic data. (Geographic Information Systems, GIS, allows us to organize all the available territorial information over the 2D representation of the terrain and support data interrogation and analysis.) In most cases, we need some sort of GIS-like tool so we can easily map data to the 3D geometry or segment the digital surface of the artwork according to various categorizations.

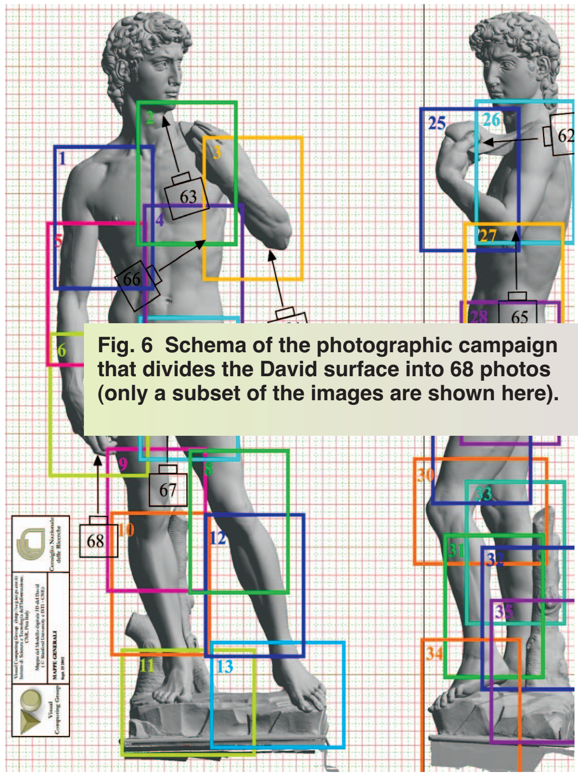

Fig. 6 Schema of the photographic campaign that divides the David surface into 68 photos (only a subset of the images are shown here).

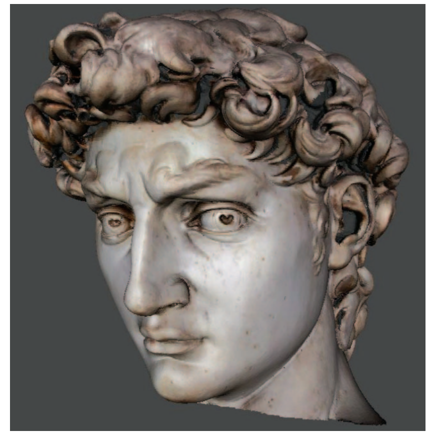

Fig. 7 Mapping of RGB images on a section of the statue's digital model (images rendered from the 3D model).

Unfortunately, the cultural heritage domain is still a niche market. It does not attract the interest of software companies. Thus, we often field requests to design and to implement tools. This complicates our work as a computer graphics research team, since our main focus should not be to produce final software products.

Another critical point is the acceptance of digital methodologies by cultural heritage restorers. They usually have a nontechnical background and are often reluctant to endorse digital methodologies. Fortunately, this negative position is easily overcome when they realize how useful these tools could be in their daily work. Although, tool usability is yet another issue we then have to address. 3D graphics and visualization tools are often complex and these potential users are generally not IT experts. Moreover, a specialization of the available instruments is often needed to fulfill specific requests. Consequently, members of a modern cultural heritage restoration staff would benefit from a substantial IT and computer graphics education (or at least a subset of them).

Fig. 8 Image of the Web-based system used to browse the RGB photograph and relief database.

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Read more about it

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The Visual Computing Lab is actively working on several projects using interactive 3D graphics (scientific visualization, volume rendering, multiresolution data modeling and rendering, 3D scanning). In particular, the Cultural Heritage domain is a major field of application of the technologies developed. Researchers of the group also are working together with art historians and restorers in a number of projects concerning digital 3D encoding, virtual presentation and computer-aided restoration of artworks.

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