

Making profitable use of the digital 3D model in the *David's* restoration

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Modern 3D scanning technologies allow the reconstruction of 3D digital representations of cultural heritage artefacts in a semi-automatic way, characterised by very high accuracy and wealth of detail [1, 2]. This technology has immediately been applied to cultural heritage, since the requirements of this field (high precision and dense sampling, joint management of shape and optical properties of the surface) fit well with the potentialities of 3D scanning technology. As we learned from the previous contribution, a digital 3D model of Michelangelo's *David* was created during the Digital Michelangelo Project [3].

The availability of an accurate digital representation opens up several possibilities of utilisation either for experts (restorers, archivists, museum curators) or for ordinary people (students, museum visitors). 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 presentations or virtual reality navigation: the classical rendering-oriented applications are still predominant [4, 5]

- 1 (see examples in Fig. 1). However, although people working in the cultural heritage field are initially fascinated by the beautiful images we can produce, they are soon asking for tools that are

more useful in their day-to-day work. We agree with them: the use of 3D models should go beyond the possibility of creating synthetic images.

An exciting opportunity is to introduce the use of digital 3D models in the restoration of works of art. The integration between 3D graphics and restoration represents an open research field and the *David* restoration project has given several starting points and guidelines for the definition and development of innovative solutions. Our work has been guided by problems and specific requests suggested by restorers. A 3D digital model can be used to support restoration in two different ways: as a *tool* for conducting specific investigations, or as a *support medium* for the archiving and integration of restoration-related information, gathered from the different studies and analysis undertaken on the work. The *David* restoration qualifies as an ideal testbed to experiment the integration of 3D graphics and restoration, since a complex series of scientific investigations has been planned for both before and after the restoration treatment. This has given us the opportunity of trying out different methodologies to support restorers/scientists with either 3D models or with synthetic images produced from digital models. The work undertaken is described in the following sections: first, we present how we have used the 3D model to increase our knowledge of the work; second, we report how we are using it as a support medium to present and archive restoration data; finally, the third section is ded-

Exposure of the David's surface to dust or other contaminants. Detail of Fig. 2.



FIGURE 1. Two different visualisation systems developed to provide interactive access to 3D digital models: on the left, the stand created by Stanford University and recently installed in the Galleria dell'Accademia; on the right, the Inspector's virtual navigation system, developed by CNR - ISTI.

icated to a more technical description of the intermediate processing phases needed to prepare the 3D data for the different applications presented.

3D data as a tool to study a work of art

As we mentioned before, the availability of a digital 3D model can support the execution of specific investigations using just a digital approach. In the *David* restoration, we performed two main "digital" investigations: the characterisation of the surface exposure with respect to the fall of contaminants, and the computation of a number of physical measurements.

Surface exposure characterisation

We designed and implemented a tool to evaluate the exposure of the *David's* surface to the fall of contaminants (e.g. rain, mist or dust). This phenomenon depends on the fall direction of the contaminant, the surface slope, the self-occlusion and the accessibility of different surface parcels. Our tool produces several qualitative and quantitative results, useful for characterising the surface of the work. The fall directions of the contaminant agents

are 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 fall distribution d_i and a point p of the surface of the model, we compute whether p can be directly viewed along direction d_i , or in other words, if we can reach p 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 1,024 random directions sampled according the above distribution. For the sake of efficiency, we exploit graphics hardware to compute whether a given vertex can be directly viewed along a direction. At the end of this process we have an exposure value for each vertex, corresponding to the number of directions from which this vertex is visible or, in other words, to an estimation of the solid angle from which this point can be reached with respect to a given cone of directions.

Fig. 2 shows some results obtained on the *David's* surface, using an α value equal to 5 degrees on the left and 15 degrees on the right. The different exposures are visualised using a false-colour ramp, with red corresponding to absence of fall

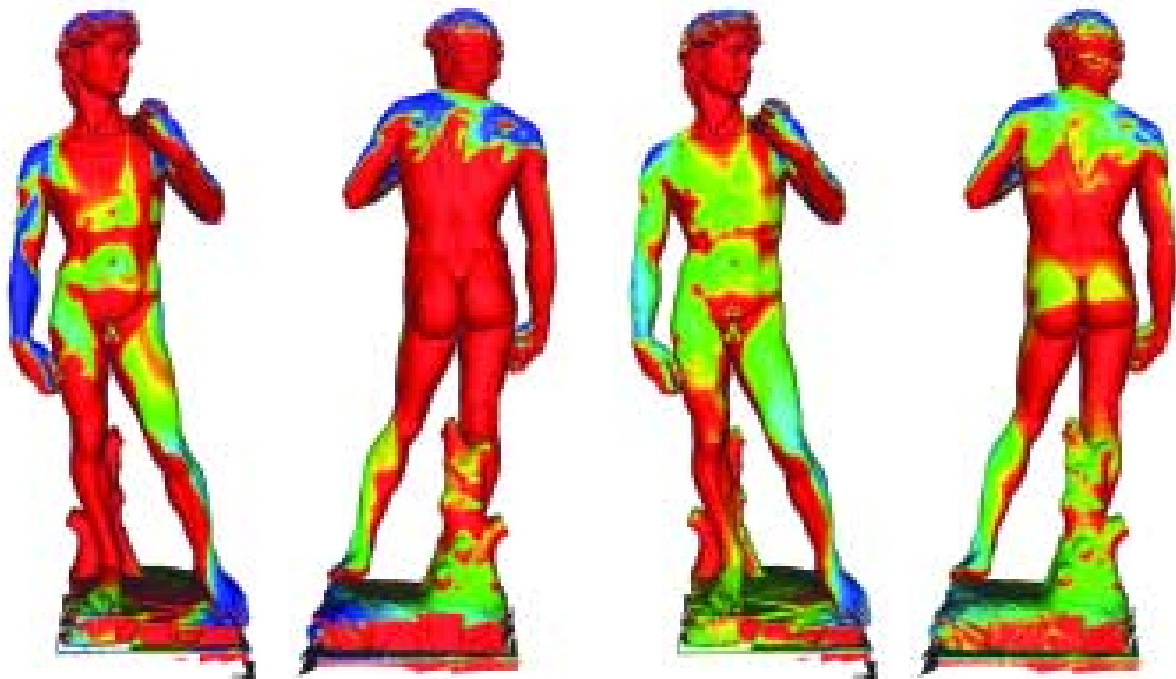


FIGURE 2. Exposure of the David's surface to dust or other contaminants. Using a false-colour ramp, this visualisation shows the different intensities of exposure produced by the simulation (red: absence of fall, blue: high density of fall) under a maximum angle of fall of 5 degrees (on the left) and 15 degrees (on the right).

and blue to high density of fall. The digital 3D model is therefore used both to compute the simulation and to present the results in a visual manner. Tables and graphs have also been produced with numerical results.

Physical measurements

Physical measurements can be computed directly on the digital 3D model, for example, the height of the *David* (the figure itself is 4.86 m, which becomes 5.16 m if we include its stone base and a total of 6.72 m with its 1.56 m pedestal), its surface area (19.47 m²) or volume (2.098 m³). Knowing the unit weight of the constituent material of the work (i.e. marble weight per dm³), the total weight (5,660 kg in the *David's* case) can immediately be computed from the volume measurement. 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 visualise the digital model. A linear measuring feature has been included in our visualisation tool (*Easy3DView*): the user simply selects two points on the *David's* surface and the tool computes the linear distance between those two points.

One of the issues under evaluation in *David's* restoration is the static condition of the statue. Some cracks on the back of the ankles give cause for concern. They could have been generated by an incorrect distribution of the mass of the statue: some historical records sustain that the original base was slightly inclined and the statue was leaning forward. An analysis of the static condition of the statue was therefore included in the series of investigations to be done before restoration. Basic data for this investigation included locating the centre of gravity of the statue, the vertical fall line of the centre of gravity, and the mass. This data was computed directly on the digital 3D model, after performing various necessary pre-processing steps on the original 3D data. The first step was to modify the orientation of the digital model in order to match it with that of the real statue (this procedure is described later in the text). The second step was to edit the digital model, since computing mass properties requires that the digital model be a closed 2-manifold surface (i.e. with no small holes in the surface). Given the high memory and computing requirement of this technique, we chose

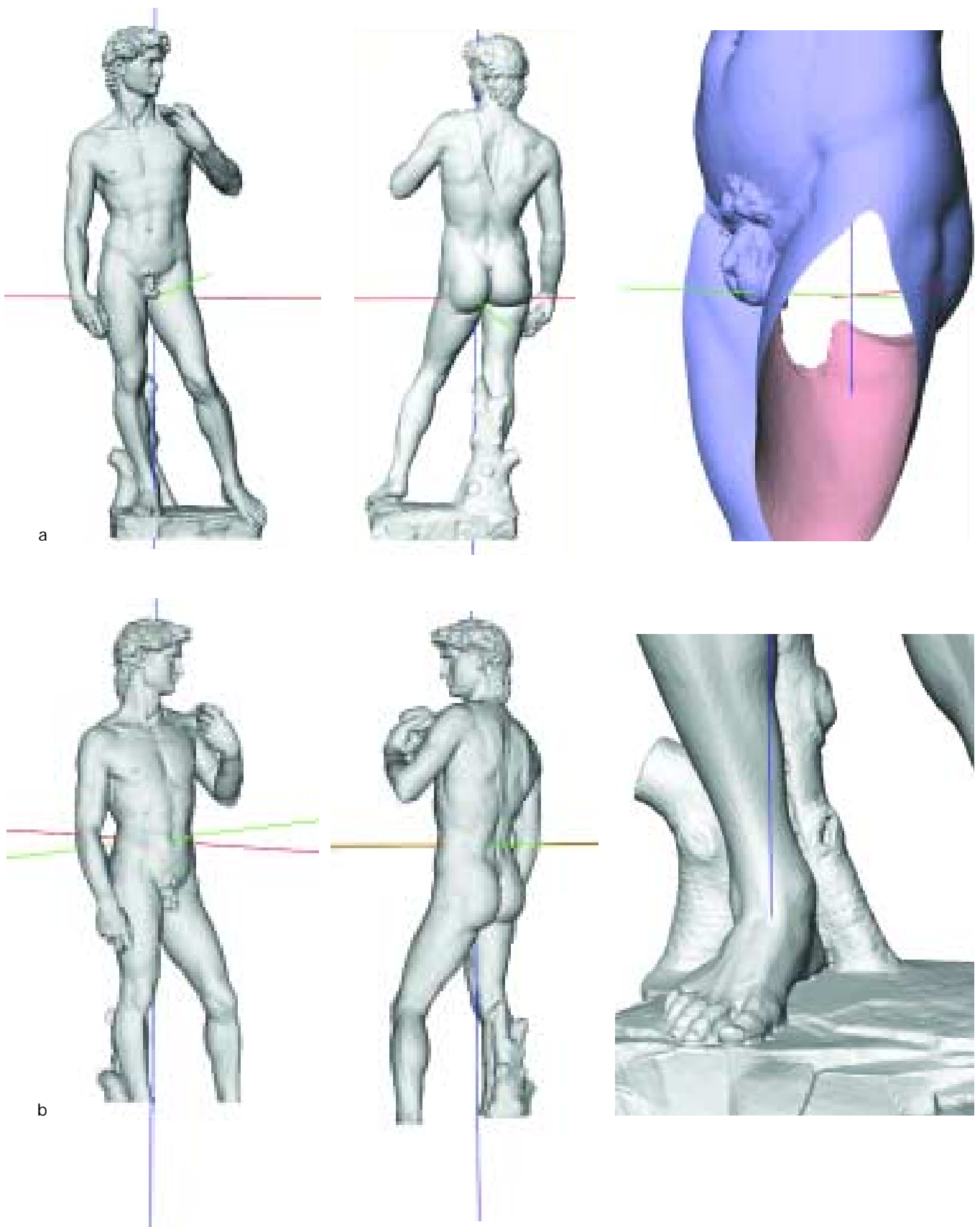
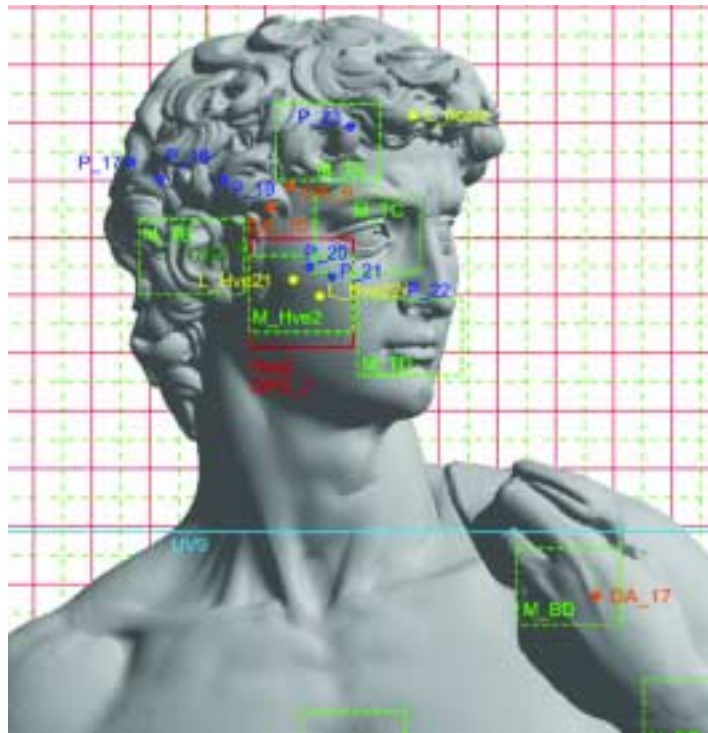


FIGURE 3. a) Calculation of the spatial position of the David's centre of gravity and its vertical projection line (in blue); b) the images below represent the evaluation of the centre of gravity truncating the statue at the height of the main cracks.

FIGURE 4. Scientific investigations were carried out on selected points or areas of the statue's surface; these locations have been mapped onto the digital model.



to work with a model of around one million faces. The approximation introduced by this simplification step [6] did not affect, in any significant way, the final computation of mass properties. The approximation error we introduced using a simplified model had a near-to-zero average (with respect to the original surface), and it was therefore almost entirely summed away during the integration process required to compute mass properties. We empirically proved this property by reconstructing models with even lower accuracy (500k and 100k faces) and finding that the computed centre of gravity positions were not significantly affected by the change of resolution of the 3D model used.

The mass properties (volume, centre of mass and the moments and products of inertia of the centre of mass) of the digital model are computed using an algorithm that exploits an integration of the whole volume assuming constant density of the mass [7]. The algorithm is designed to minimise 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 ascertained that the statue's centre of gravity lay in the interior of the groin, approximately in the pelvis (Fig. 3a). The vertical projection of the centre of gravity on the base of the statue (i.e. the sculptured rocky base on which the *David* stands) is the blue line, which exits from the marble at the back upper part of the left thigh and re-enters the marble on the right foot. We also estimated the statue's centre of gravity without its base (truncating the statue at the height of the main cracks): the new position of the centre of gravity is illustrated in Fig. 3b. The projection of the vertical line of the centre of gravity on the statue base has been recorded with a large-format plotting¹ produced with our *Cavalieri* [8] drafting tool (briefly described in the paragraph on *Producing renderings*).

3a

3b

3D models as a medium for archiving, integration and visualisation of restoration-related information

A second important use of 3D models is as an instrument to record, organise and present restoration data. During the *David* restoration campaign, a number of scientific investigations were con-



FIGURE 5. Mapping of the UV images on the respective section of the David digital model.

ducted, which are described in detail in this publication. All the results produced by these investigations are being organised and made accessible through a system implemented with web technology, to simplify access to the data. The 3D model of the *David* was used to build different spatial indexes for the above data (Fig. 4), indicating their location on the surface of the statue and supporting hyperlinks to web pages describing, in every 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. A good example of this was the ultraviolet (UV) imaging investigation. Images produced under UV lighting are very important for detecting the presence of organic materials (e.g. wax) on the marble surface, which have to be removed with the appropriate solvents. The UV investigation carried out by the Opificio delle Pietre Dure produced many 2D images taken from different angles. These images can be mapped onto the 3D surface using an approach which computes the inverse projection and camera specification from each single photograph and com-

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Another important source of data was the high resolution photographic survey of the *David*, carried out by a professional photographer with digital technology and according to the specifications given by our group. The photographic sampling was planned as shown in Fig. 6. The photos were taken to record the visual state of the statue before restoration. These RGB (red, green, blue) images can also be mapped onto the 3D mesh (Fig. 7) with the same methodology used for UV images [9, 10]. In addition, a detailed graphic survey of the condition of the *David's* surface was carried out. An accurate mapping, drawn onto the above-mentioned high resolution photos and covering the entire surface of the statue, was made of the following features:

- imperfections of the marble (small holes or veins);

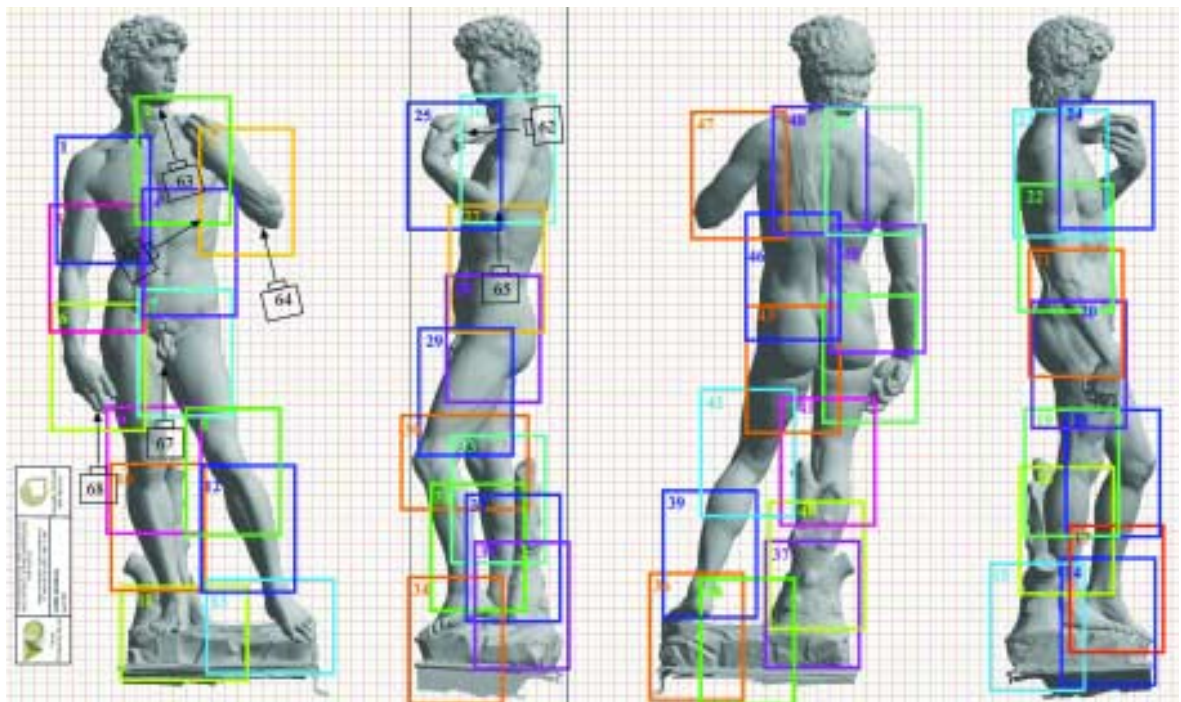


FIGURE 6. Plan of the photographic campaign, which divides the David surface in 68 photo shots.



FIGURE 7. Mapping of RGB images onto the David digital model.

- presence of deposits and stains (brown spots or traces of rain staining);
- surface deterioration;
- remaining traces of Michelangelo's workmanship.

The above features were mapped on transparent acetate layers positioned over each printed photo (in A3 format). We therefore have four different graphic layers for each of the high resolution photos. These graphic plottings have been scanned, aligned (roto-translation + scaling) on the corresponding RGB image, and saved at the same resolution as the RGB images. A web-based system has been implemented to browse the RGB images and to plot in overlay any mapped layer selected by the user (Fig. 8). It was decided to show the mappings in overlay on the RGB images, thus using a 2D-based visualisation approach, instead of trying to map features and RGB images on the 3D surface. This choice was justified by the large amount of information contained in the 2D photos and graphic plottings (each one is a 5M pixels image), which makes mapping and interactive rendering onto such a complex 3D surface very hard work. In this case, the 2D space is much more suitable for mapping the data, since access

to the latter will be selective (the user will be able to browse over small regions of the *David's* skin). The 3D model has, instead, been used as a spatial index for the set of images.

Processing the digital 3D model

The 3D digital model of Michelangelo's *David* was built using 3D scanning technology and is the result of the fusion of a very large set of range maps in a single continuous triangulated surface. Triangulated surfaces are the most common 3D data representation. A standard criterion to measure the complexity of a triangulated surface consists in giving the number of elementary triangles that build it: 56 million in the case of the digital *David*.

We performed different processing tasks on this data. The first was to reduce the data complexity and produce new instances of the initial raw mesh at different levels of detail (LOD), since the size and accuracy of a digital representation must be tuned according to the needs of the different applications. The second task was to "clean" the digital model by editing it, for example, by removing all the small holes contained in the tri-

angulated surface. Many different renderings were then produced from the digital representations for restorers to use, often using our *Cavallieri* tool [8]. Finally, some selected 3D acquisitions were carried out on a small group of areas of the statue's surface, in order to record the level of roughness and deterioration.

Reducing the complexity of the digital representation

Different uses of the digital representation often need an adequate size of the 3D data. In order to make the original *David* digital model more easily manageable, we applied our simplification technology [6] to reduce data complexity to the

size and accuracy needed by each different use or application of the digital model. The simplification of a triangulated surface is performed by the iterative removal of the mesh element (vertex or triangle): at each step, the algorithm automatically deletes the element whose removal introduces the smallest error. Our solution is highly efficient and accurate and is the only one able to manage very large surfaces with great accuracy. Some results are presented in Fig. 9.

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Editing the 3D digital model

3D models produced with 3D scanning technology are often edited to improve data quality, for example, to remove noise or improve mesh topol-

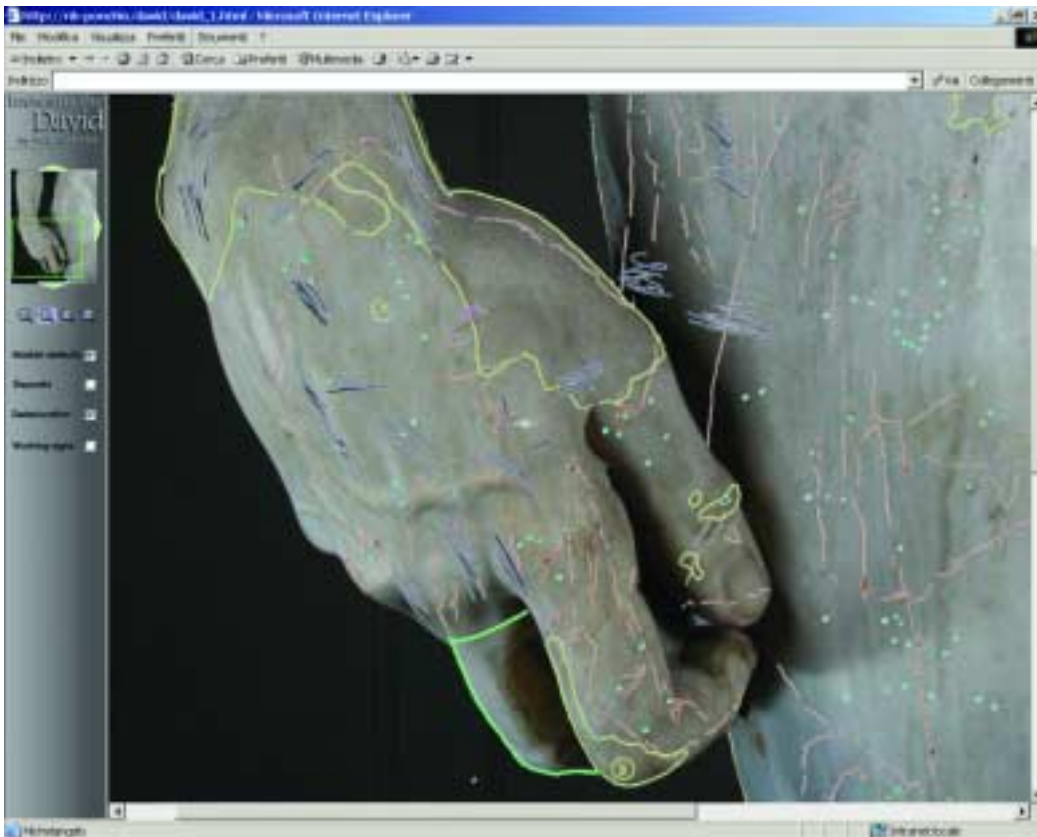


FIGURE 8. A preliminary image of the web-based system to browse the RGB photographs and the mappings drawn by A. Parronchi.



original data,
~161,000 triangles
(just the rendered section)

quadr.err.=1e-2,
~39,000 triangles

FIGURE 9. A comparison of different models produced with our simplification tool. The accuracy is proved by the very subtle changes of the shape, even when a substantial simplification rate is used (the far right surface is simplified with a 26:1 reduction factor).



quadr.err.=1e-1,
~21,000 triangles

quadr.err.=10,
~6,000 triangles

ogy. Some editing actions were needed to perform the digital computation of physical measurements (mainly, the volume of the statue and its centre of gravity).

The first task was to modify the orientation of the digital model in order to match it with that of the real statue. We measured the orientation of the real pedestal and checked it with the orientation of the base of the digital model. This resulted in a non-perfect vertical alignment of the digital model with respect to the real one. This is a common situation, since 3D-scanned data give a very accurate sampling of the relative geometry, but they are given in a representation

space that depends on the location of the scanner. A precise orientation to a given reference system has to be imposed on the scanned model (i.e. a simple rigid roto-translation). The accuracy of the vertical alignment of the digital model is very important for the correct interpretation of its mass properties. We corrected this alignment, by computing and applying the proper rotation to the digital model to match it with the real position of the statue.

The second task was to remove all small holes from the digital surface. Producing a hole-free surface directly is in most cases impossible, since a complex work of art presents many small regions



FIGURE 10. Photograph of the reproduction of the David's head, reconstructed from the digital model (reproduction scale 1:2) with a stereolithography device.

that cannot be properly sampled/reached by the scanner (e.g. the curls of the *David*). On the other hand, a hole-free representation is needed for a number of different uses: many physical reproduction devices require a hole-free input (Fig. 10 shows a reproduction of the *David's* head obtained with a stereolithography device). The computation of mass properties (volume, centre of gravity) also requires the digital model to be a closed surface. For this purpose, we used the algorithm presented in [11] to close all the open holes in the digital surface. This approach has been implemented and included in our proprietary scanning and post-processing tools [12].

Producing renderings – images and prints

The availability of an accurate digital model allows the production of a number of different *images* (called *renderings* in computer graphics jargon), which can be used both as documentation or as working tools for the restorers/scientists involved in the restoration. Images were produced using two software tools developed by our laboratory: *Easy3DView* and *Cavalieri*.

Easy3DView is a browser supporting the interactive manipulation and rendering of triangulated 3D surfaces. It runs on low cost PCs, offers the standard visualisation features (rendering mode:

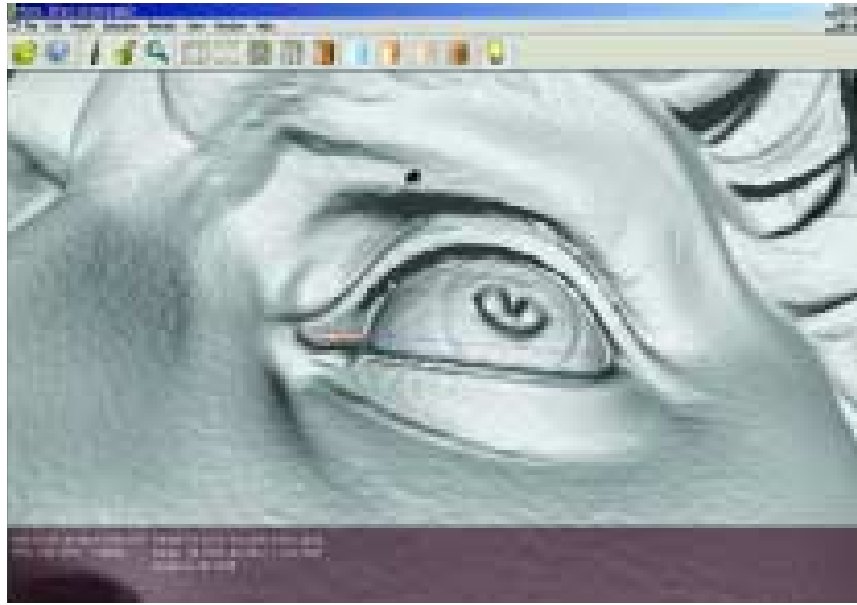


FIGURE 11. Screen dump of the Easy3DView interface (above) and printout produced with Cavalieri to define the regions taken into account in the scientific investigations (below).

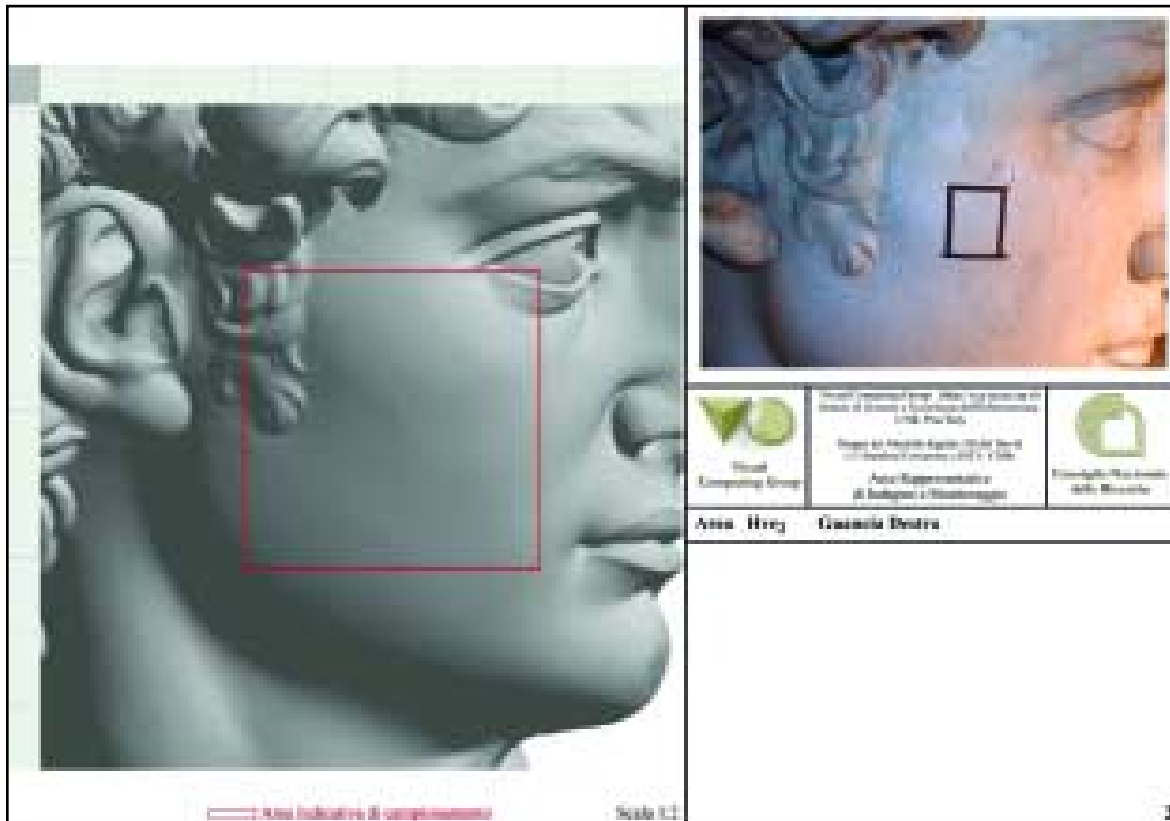




FIGURE 12. The four regions scanned with the Minolta laser scanner: face, toes of left foot, portion of right hand, and left shoulder.

shaded, wire frame, points; view setting; light position setting; etc.) and permits taking measurements on the 3D mesh by selecting pairs of points (an example is shown in Fig. 11, where the width of the *David's* left eye has been computed: 99 millimetres).

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Cavaliere has been designed with a different purpose: to produce very high resolution images to be printed with a plotter from high resolution 3D-scanned models [8]. Here the focus is not on interactive rendering, but on how to define the

specification of a given large format printout (i.e. its reproduction scale, the use of orthographic or prospective projection, the selection of a given view, the selection of cut through sections, etc.) in a user-friendly manner, and how to produce the corresponding raster image.

Further 3D scanning

A partial scanning campaign was run to acquire new digital models of certain areas of the statue.

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The aim of this work was to record the condition of the marble surface in areas where deterioration was more intense. We performed the new acquisition using a Minolta Vivid900 laser triangulation scanner and the Visual Computing Lab post-processing tools. The areas covered were the face, the left shoulder, a portion of the right hand, and the toes of the left foot (Fig. 12). The four areas were scanned at maximum sampling resolution (approximately 0.25 mm inter-sampling distance); around thirty range maps were shot to sample either the shoulder or the foot. These range maps were aligned [13] and fused with a volumetric method [14], using a voxel size of 0.3 mm in reconstruction. Smaller portions of each of these areas were also sampled with a much more accurate device, able to measure the roughness of the surface.²

Conclusions

We have presented some examples on the use of a 3D digital model within the framework of a restoration project. As shown, the 3D representation has been used both to conduct specific investigations and as a support medium for the archiving and integration of restoration-related information.

The adoption of a similar approach in a standard restoration project is affordable, as the reconstruction of digital 3D models has become less and less costly. While the cost of earlier scanning projects was rather high only a few years ago, scanning a work of art with state-of-the-art hardware and software technologies today only takes a few days. For example, we recently completed a full scanning of the 1.60 m bronze statue of the Minerva of Arezzo in just one week,³ which also included the raw data post-processing.

The main difficulty is not the cost of scanning, but rather the lack of tools oriented towards restoration or, generally speaking, those that could facilitate the use of 3D graphics in the cultural heritage domain. A clear example can be seen in the use of 3D graphics to present other data: the tool would be very similar to that used for

geographical data management. Most restoration projects which produce and use 3D data show the need for some sort of GIS-type tool that would allow easy mapping of the available data to the 3D geometry, or would segment a 3D surface according to some kind of categorisation of analogous surface conditions. Unfortunately, the field of cultural heritage is still a narrow 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 produced by a professional software developer (e.g. the *Cavallieri* system [8]), and this makes the work of a computer graphics-oriented researcher harder. Another critical point is the acceptance of digital methodologies by those working in cultural heritage. They usually have limited knowledge of information technology and are often sceptical of or reluctant to endorse digital methodologies. Fortunately, experience has taught us that this initial negative reaction can easily be transformed if computer graphics experts are able to offer them not only attractive images, but also tools that they can use effectively in their day-to-day work.

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Notes

¹ Cf. Part III, Marchetti, Fig. 3, p. ???.

² Cf. Part III, Reports on single investigations, investigation 4.

³ Data on our Minerva scanning times is published on the Digital Minerva project web page: <http://vcg.isti.cnr.it/projects/projects.htm>

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