

Mapping highly detailed color information on extremely dense 3D models: the case of David's restoration

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Abstract

The support of advanced Information Technology (IT) to preservation, restoration and documentation of Cultural Heritage is becoming a very important goal for the research community. Michelangelo's David was one of the first applications of 3D scanning technology on a highly popular work of art. The subsequent restoration campaign, started in 2002 and concluded in 2004, was also a milestone for the adoption of modern scientific analysis procedures and IT tools in the framework of a restoration process. One of the focuses in this restoration was also methodological, i.e. to plan and adopt innovative ways to document the restoration process. In this paper we present the results of an integration of different restoration data (2D and 3D datasets) which has been concluded recently. The recent evolution of HW and SW graphics technologies gave us the possibility to interactively visualize an extremely dense 3D model which incorporates the color information provided by two professional photographic campaigns, made before and after the restoration. Moreover, we present the results concerning the mapping, in this case on the 2D media, of the reliefs produced by restorers to assess and document the status of the marble surface before the restoration took place. This result could lead to new and fascinating applications of computer graphics for preservation, restoration and documentation of Cultural Heritage.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Color, shading, shadowing, and texture

1. Introduction

Michelangelo's David is one of the most popular art icon of our age, a rather old friend who deserves cure. The statue life was not so easy as one can imagine, since several accidents and the passing of time left traces on its surface. The statue was always kept under control and subject to several restoration actions in the past. At the end of last century, a major restoration action was planned to allow it to begin the new millennium with an improved look and a complete assessment of its conservation conditions. The restoration planned was a light one, mostly focused on the removal of dust, spots and other deposits accumulated in the years on its surface, and on the replacement of the plaster fillings of some fractures (e.g. the ones filling the small gaps of the fragments of the arm broken in XV cent.). Therefore, no major change of the shape was planned, but just a selective cleaning which should have changed its surface appearance. Nevertheless,

the restoration was preceded by an intense and very complete set of scientific investigations, aimed at making a severe screening of the statue conditions [BFMS04]. The interest of the curators to run a complete scientific assessment of the statue condition, together with the availability of a digital 3D model of the statue (scanned by the Stanford's Computer Graphics Group in the framework of the Digital Michelangelo project [LPC*00]), made it possible to adopt a number of ICT technologies to both analyze and document the statue conditions and the restoration action [BFMS04, CCG*04].

In particular, the David restoration project (started in Florence in 2002 and terminated in 2004) was a milestone for the definition and development of solutions which qualify a modern restoration, by integrating a number of different scientific approaches under the same global focus (IT was just one of those disciplines). Among other tasks, we were asked to document the status of the statue before and af-

ter the restoration in a manner which should be both rigorous and able to transmit the information to the experts and the public in a simple and intuitive way. The opportunity to experiment modern visual data management approaches was immediately evident. The starting point was the 3D model produced by the Digital Michelangelo project (a surface model, 56M triangles, acquired with triangulation-based laser scanning technology). Since the restoration was mostly a cleaning task and perceptible modifications of the shape of the artwork were not forecasted, we did not plan a new 3D scan after the conclusion of the restoration work. The changes were going to occur mostly in term of different appearance of the surface. For this purpose, a high quality photographic essay of the pre- and post-restoration condition was the starting point and one of the major sources of data (see Section 4). Moreover, another important piece of information was the analysis of the status of the surface done by the chief restorer, i.e. a clear characterization of the degradation status done on the entire surface extension. The restoration supervisor asked for an innovative approach to replace the classical textual report (usually written around a few images and drawings). For this purpose, a joint group composed by the restoration supervisor, the restorers and the IT staff discussed several options and agreed on the approach described in Section 5. Unfortunately, at that time the only possibility was to implement it through the drafting of several manual reliefs. The following step was how to manage all those data (a huge 3D model, around 150 high resolution images and several hundreds reliefs) in an interactive manner, possibly using a 3D approach to data presentation. Due to the limits in algorithms or hardware resources, interactive visualization of highly dense 3D and 2D data has become possible only recently. This has given us the possibility to process most of the data acquired and to present them interactively. The basic components, that only recently have become a robust technology, are the one needed to build up and render a 3D model with highly detailed geometric and color information. With *highly detailed* we mean more than 50M faces and more than 200M texture data. But we still have some limitations in managing some of the available data, i.e. the line-based reliefs whose mapping on 3D geometry is still complex. The solutions devised to present the data are presented in Section 6 and 7. Finally, conclusions and some remaining issues are illustrated in Section 8.

2. Related Work

A number of projects regarding the use of new technologies in Cultural Heritage have been presented in recent years (see the many symposia and conferences focusing on this domain). Among the general IT domain, 3D computer graphics has a consolidated reputation as being one of the major IT tools for the study and management of CH artifacts. More specifically, 3D scanning [BR02] is nowadays accepted as a major source of digital data to represent the CH artifacts of interest and to support to the work of experts for several

applications, like preservation, documentation, prototyping, visualization [LPC*00, BRM*02, STH*03, BCC*05]. Beyond the classical uses which focus on visual presentation, other approaches have been proposed [PSS05] to help in a very concrete way the restoration process, or to provide comprehensive database for diagnostic and restoration purposes [GPCM05]. A comprehensive survey of the many different approaches proposed to integrate 3D data representation in the framework of CH management goes well beyond the scope of this paper. We give in the following just a few citations to representative papers which focus on the main technical instruments needed to cope with 3D models and color data. How to map efficiently and accurately a set of 2D images on a 3D model is a classical research topic, where intense research has been done in the last years. Several approaches have been proposed [BMR01, CCS02, Bau02], all aiming to produce a realistic texture map from a set of photos. The major issues are usually how to build up an optimal parameterization of the surface on a texture space, and how to integrate the multiple and redundant 2D data (many input images) into a common texture space. Other approaches focus on more accurate techniques to gather the reflectance properties of the object material [Goe04], therefore going beyond the naive apparent color gathered with digital photography. Unfortunately, all these methods work very well when we have a small number of 2D views, simple geometry and/or controlled illumination. More recently, new solutions have been proposed to manage the alignment of a big number of photos on a 3D geometry [FDG*05] and to compute weighted color values from all these samples [CCCS07]. These solutions have been already applied in the context of Cultural Heritage related projects (see for example [BCC*06]).

The evolution of inexpensive GPUs and the birth of new algorithms for the visualization of extremely dense 3D models [Pri00, RL00, BK03, CGG*05] led to the possibility to display color by assigning a color value to each vertex of the geometry (color per-vertex), rather than building up several RGB textures, mapped to a high-resolution 3D mesh [BGB*05, DBH00, DPF01]. These approaches have two positive advantages: they do not require a parameterization on a texture space and encode color information in a more space-efficient manner on all those cases where the 3D model resolution is approximately the same as the color data resolution.

3. The 3D model

The Stanford's Digital Michelangelo project [LPC*00] produced a huge amount of different data (3D models, 2D RGB and UV images). The result of the scanning campaign was a very detailed 3D Model (56 million triangles, reconstructed from 4000 range images using a distance field with 1mm. cell size). The Digital Michelangelo project acquired also data on the surface color, but those data were not usable

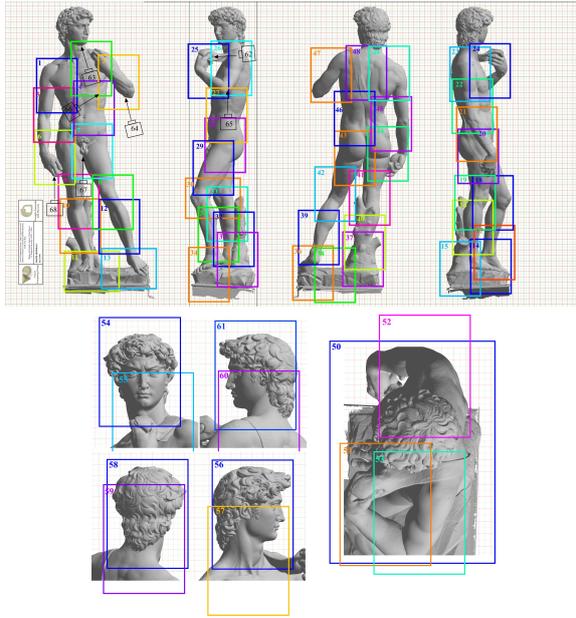


Figure 1: Examples schema of the photographic campaign, describing the coverage of the set of photos.

for our purposes both for some apparent contamination from an UV light source used while taking the RGB images and for the specific needs of the restoration documentation (two nearly identical set of views were requested being taken, both before and after the restoration, from known positions on the scaffolding built around the statue). The evolution of the scanning technology would have permitted nowadays to have a slightly better sampling resolution and an higher resolution final model. Unfortunately, the cost of scanning again such a large surface from a scaffolding was considered too expensive for the limited restoration project finances. The available Stanford's 3D data quality was considered sufficient for the purposes of the restoration and documentation.

4. Photographic acquisition

To obtain a concrete and accurate visual survey of the status of the surface, a high-resolution photographic survey of the David was performed by a professional photographer (Studio Rabatti and Domingie, Florence). The photographic sampling was done according to the specifications defined jointly by the IT staff and the restoration supervisor (a graphic representation of the planned photo survey is shown in Fig. 1). Photos have been taken in two different periods (before the start of the restoration and at the very end), requiring around one complete week of work each. The amount of 2D data collected (61 images, res. 1920x2560 to document the pre-restoration status; 68 images, res. 2336x3504 for post-restoration status) was about



Figure 2: Examples of images from the pre- and post-restoration campaign.

800 Mega pixels. Some sample images from both sets are shown in Figure 2.

5. Restorers' analysis: how to take trace of the condition of a complex surface?

The survey of the conservation status of the surface was one of the requested documents which should have been produced in the restoration process. The problem was how to plan that survey in order to make it possible the integration of the data produced with the digital data (2D or 3D). Nowadays, the more direct solution could be to design a tool which allows the restorer to draw the survey directly on the 3D model, i.e. using a painting/drafting system to make the relief directly onto the 3D model. Four years ago, the status of the technology did not allow us to even consider this approach. Another hard constrain was the limited experience of the restorers with IT and CG technology, and therefore this solution was immediately abandoned. The approach followed is therefore based on a manual relief drafting, followed by a digitization phase and a final mapping. The restorers have performed a precise graphic survey on the status of the David's surface. They drew very accurate annotations on the high resolution photos (the ones from the photographic essay, see previous section), 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 the restorers on transparent acetate layers positioned onto each printed image, using different color to indicate the same phenomena in the different sheets. Therefore, we have 4 different graphic layers for each one of the 61 high-resolution photos (documenting the pre-restoration status). An example of the graphic relief is shown in Figure 3.

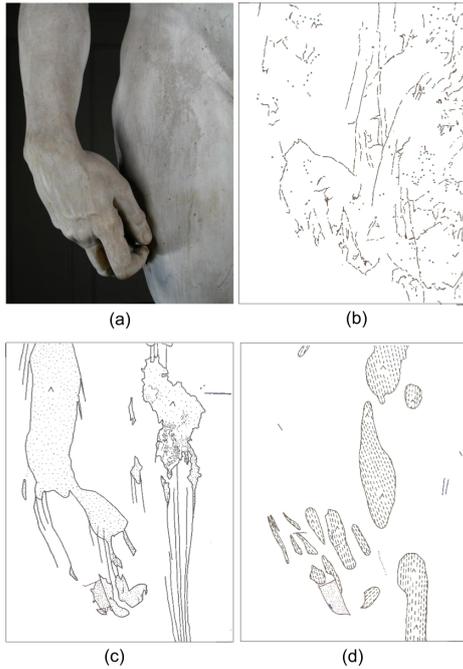


Figure 3: An example of an image of the photographic set with the corresponding (b) imperfections, (c) deposits and (d) consumption reliefs.

These graphic reliefs on A3 acetate sheets have been scanned (using a commercial A3 flatbed 2D scanner), registered on the corresponding RGB image (the roto-translation needed to have a correct matching between each relief and the corresponding digital image), and saved at the same resolution of the corresponding RGB image.

6. Data Mapping

The amount of high quality data described in the previous sections was really a valuable documentation of the restoration process. In order to visualize, analyze and compare data with a paper-less mode, two approaches were chosen: (a) 'classic' 2D mapping of the reliefs on the corresponding 2D RGB images (implemented using web-based technologies), and (b) mapping of the RGB data (pre- and post-restoration images) on the digital 3D model. The 2D mapping was chosen as a easy way for experienced and unexperienced users to access the photographic and reliefs archive, and also because at restoration time there were several constraints to the projection and visualization of color on 3D models. More recently, new techniques and tools made it possible to map all the images and visualize dense geometry interactively. In the next subsections we describe the two different visualization approaches and, very briefly, the new solutions recently proposed and used to build up the mapping.



Figure 4: A screenshot of the web based system to visualize reliefs mapped on 2D images



Figure 5: Images of the same portion of the statue, taken before and after restoration: in this case the position of the camera is different

6.1. Mapping reliefs on 2D images

An intuitive web-based system was created, that can be delivered either on DVD or on internet[†]. Following the scheme provided by the photographic campaign, the user can choose any of the provided views, and then visualize the corresponding photo and, selectively upon his/her choice, the superimposed reliefs related to imperfections, deposits and deteriorations (see Figure 4). Images can be visualized with different zooming factors, so the high detail can be appreciated at its best. A screenshot of the system is shown in Figure 4: in this case, the *deposits* relief is superimposed to the selected image.

It's also possible to load the corresponding photo taken after the restoration. Unfortunately the position of the camera in the two acquisition campaign usually was slightly differ-

[†] Due to copyright issues, the material is now distributed only on DVD.

ent (an example is shown in Figure 5), since it was really impossible to shot the post-restoration images from exactly the same views used in the pre-restoration campaign. These small view differences are not a problem for a human observer, but make it impossible to superimpose the pre- and post-restoration images, or to superimpose the reliefs to the post-restoration images. A possible solution to this problem is sketched in Section 7, i.e. after mapping the RGB data to the 3D model, as shown in Section 6.

6.2. Mapping RGB data on the 3D model

There are two main issues related to the projection of the color information on a 3D model:

- the alignment of each photo in the set to the 3D model. This action corresponds to the estimation of the *intrinsic* and *extrinsic* camera parameters. In most cases the parameters are not known in advance;
- the creation of a set of rules to calculate an interpolated color value assigned to each vertex of the model, taking into account the weighted contribution of all the photos which project on the same surface locat.

Both tasks imply the manipulation of a huge amount of data, and have to be performed with the minimum human intervention, as fast as possible to reduce personnel costs. The issue of registering uncalibrated images to a 3D model has been discussed in several papers [LWG97, KNZI02, JC04]. Completely automatic registration can be achieved only under particular assumptions (e.g. [LHS00]), otherwise user intervention is necessary. Algorithms which estimate parameters need some correspondences between the image and the 3D model. After this approximate selection, an error minimization method is applied to find the best possible alignment. We developed a tool which allows users to load both the 3D model and all the photos, creating an Alignment Process whose data (correspondences coordinates, parameters of aligned images) are saved in an xml file.

One of the most useful features is the possibility to set correspondences not only between a photo and the 3D model, but also between photos (*image-to-image* correspondences), using the overlapping image sections. These *image-to-image* correspondences are used by the alignment application to infer new correspondences with the 3D model. This was particularly useful for the David case, because in some parts of the statue (abdomen, legs, back) it was very hard to find geometric features to set correspondences to the 3D model (see Figure 6). On the contrary, the small spots on the marble surface were used to find robust *image-to-image* correspondences in the overlapping parts of images and in a very fast way. A comprehensive presentation of all the features of the alignment tool is contained in [FDG*05].

Once calibration data have been estimated (see Figure 7), we have to *reconstruct* the color information as a weighted average of all the overlapping images and to *project* it onto

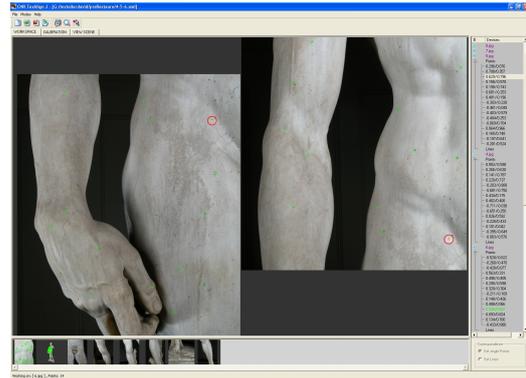


Figure 6: Screenshot of our Image Alignment tool with an example of partially overlapping RGB images (red circles indicate an image-to-image correspondence).

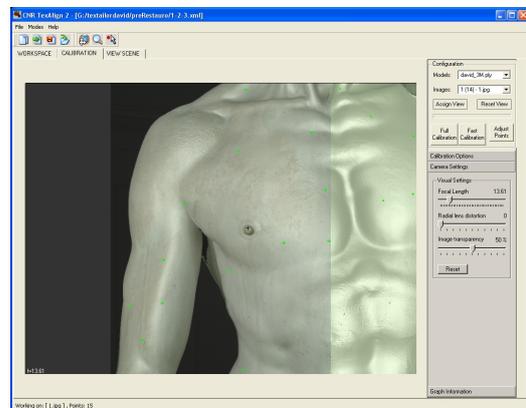


Figure 7: Screenshot of our Image Alignment tool: an example of an image aligned to the 3D model.

the 3D model. As previously stated, texture mapping could not be used without severe sub-sampling of images. Hence, since a very dense 3D models is provided, *color per vertex* is the more proper choice to preserve both geometric and color detail.

Knowing the camera projection parameters, it is easy to determine if (and where) a point on the surface does map inside any of the source photos. In this way it is possible to assign the color, taken from the corresponding location on the 2D photo space, to a point onto the surface. The real problem is when, due to the redundancy of the photo sampling, the same surface point can take the color from many sources images. To solve this, we developed a system able to evaluate the *quality* of each contributing pixel using various metrics and able to compute the appropriate color using a weighted mean. The mapping tool, starting from the set of input RGB photo, the 3D model and the calibration data, automatically creates a weighting mask for each photo



Figure 8: Example of a weight mask (on the right) calculated from the photo on the left. The weights represent the quality of each pixel, expressed as floating point value (in the image on the right, the weights are rendered using gray values, white being the highest quality for this photo).

that represent a *per-pixel quality*. The weight is calculated as the combination of three main metrics, which measure for each pixel: how orthogonally the surface is sampled (angle between surface normal and view direction); how far is the surface from the camera (distance from viewpoint); and how far is the pixel from image borders and object discontinuities (geodesic distance from borders and silhouettes, areas of minimal quality). An example of the mask calculated for the given photo is shown in Figure 8. The color value assigned to each vertex is a *weighted sum* of the contributions from all images. With this weighting mask we can efficiently use all the redundancy present in the source images to reduce illumination artifacts and incoherence between different images, while at the same time maintaining as low as possible the blurring effect. Another important issue was the need to deal with a big amount of geometric and color data: both the 3D model and the photographic dataset were too big to be kept in main memory. Given the characteristics of locality and modularity of the blending and mapping algorithm, it was easy to develop an out-of-core strategy able to deal with such large datasets. More precise explanation of all the features of the mapping tool can be found in [CCCS07]. After the color projection we obtained two 56 Million triangles colored models. Two possible uses of these 3D models are shown in the next section.

7. Advantages of improved visualization

The most intuitive use for the two 3D models is interactive visualization, which gives the user the possibility to analyze the appearance of the statue before and after restoration from any arbitrary point of view. Interactive visualization is made possible by the multiresolution technique presented in [CGG*05]; built over this data representation approach,



Figure 10: Left: one of the images of the pre restoration set; center: the corresponding image in the post restoration set; right: rendering of post restoration 3D model from camera position of pre restoration image

the Virtual Inspector tool provides a framework which allows the easy inspection and virtual manipulation of a complex and highly detailed 3D model.

A screenshot of the application is shown in Figure 9. The pre- and post-restoration models are shown on the left and right side, respectively. The user can easily change the model position and the illumination, in order to frame arbitrary points of view. The main differences in the marble surface conditions can be seen in a very intuitive way. Another interesting possibility is to render the model from arbitrary points of view. For example, we could use the camera parameters estimated for a photo being part of the pre-restoration set and render the post-restoration model from the corresponding camera position. In this way we can obtain an image of the restored model which is perfectly aligned to the starting pre-restoration photo, resolving the issue mentioned previously in Section 6. An example of this particular mapping is shown in Figure 10, where the left-most image is taken from the pre-restoration set and the central image is the corresponding one from the post restoration set. It can be easily observed that the point of view is slightly different, and superimposition is impossible. The right side image is a rendering of the 3D model with post-restoration color from the camera parameters estimated for the left side image. Now, this synthetic image could be very useful not only for superimposition of re-restoration reliefs but also to try to reproduce a similar illumination condition, which was slightly different between the two sets.

8. Conclusions and future work

In this paper we chose the David as a representative case to show that the advance of new IT and CG technologies can continuously provide new means to support restoration and documentation of Cultural Heritage. The possibility to map a large set of RGB images on a very detailed 3D model can be very useful not only in terms of documentation and visual comparison, but also for the support of the restoration: for example, the restorer could directly work



Figure 9: Screenshot of the Virtual Inspector visualization tool.

on the colored 3D model to sketch reliefs, spot particular points, extrapolate indications about the material. One weak point of our current color management approach on 3D models is the dependency from the quality of the photo set; if the photo set doesn't cover parts of the geometry, no color value can be assigned to the corresponding vertices. New texture synthesis approaches have been recently proposed for filling texture gaps, and could be included in the approach here presented to synthesize plausible values for the missing surface regions (but it has to be mentioned that in CH management curators are usually against any value which is synthesized rather than sampled). Moreover, lighting conditions can influence the final result: if the photos are taken under different illumination, or when there is insufficient overlapping to *blend* the different color samples, a color discontinuity will be visible after projection on the 3D mesh. Some examples about these aliasing are shown in Figure 11. Some solutions to these issues can be: a more careful photographic acquisition (i.e. under a controlled illumination) and the adoption of more sophisticated techniques to estimate illumination and material features from the acquired photos.

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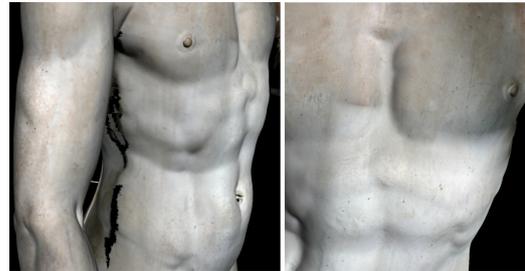


Figure 11: Example of imperfections on the colored model, due to the quality of the input photo set: leftwards, black parts are surface regions which were not covered by any photo; rightwards, the color jump on the chest is due to different illumination and insufficient overlapping between photos.

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