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Documenting and Monitoring Small Fractures on Michelangelo's David

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1. Introduction

The Polo Museale Fiorentino (the authority in charge for the management and conservation for all public museums in Florence, Italy) has started an investigation and monitoring project over the small fractures on the lower part of the Michelangelo's David. The presence of this series of small fractures is known since several decades and they have been already studied in the framework of the last restoration of the David (BRACCI et al., 2004); we briefly report on Section 2 the current knowledge concerning those damages.

A renewed interest in the assessment of the status of those lesions has risen while planning some investigations concerning the seismic stability of the Galleria dell'Accademia museum and of the potential danger in the case of an earthquake to the masterpieces conserved in the museum.

Polo Museale Fiorentino asked to Istituto di Scienza e Tecnologie dell'Informazione (ISTI-CNR) to execute a digital sampling of the *visible evidence* of those lesions, aimed to both assess the current conditions of the marble surface and to design a methodology for the digital sampling that could also be used for monitoring along time the possible evolution of the phenomena. This digital sampling is just a portion of a more complex assessment study, which includes also structural analysis, tomography, etc.

We have therefore planned a digital sampling at the best of current technology. Most of the lesions are just very, very thin apparent cracks in the marble mass (in many cases, it is not clear if they are just superficial defects of the marble or an indication of severe stress over the stone). Obviously, we have selected one of the best 3D sampling instruments for performing a complete 3D scanning of the two regions of interest (see Figure 1). Since most of the cracks are well below the current sampling capabilities of 3D acquisition systems, we also planned the acquisition of high resolution images. Those images are a document by themselves, but obviously we also designed the photographic sampling with the secondary goal to map those information over the digital 3D model.

Our goal is therefore the creation of a complete data base of 3D models (sampling the whole regions affected by the cracks at different resolutions), which should become the main digital document in the hands of the experts to support further analysis and study on this phenomena. The preliminary results of this action (started on November 2009) are presented in the following chapters.

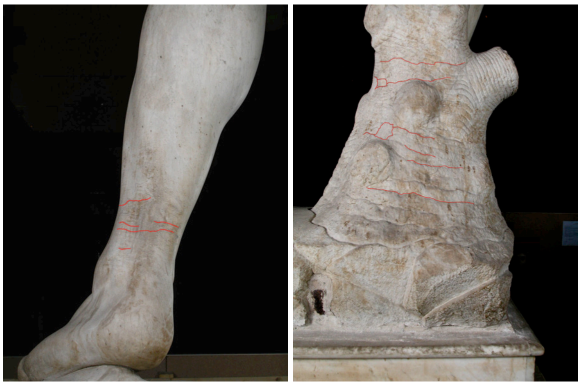

Figure 1: *The two images show the regions affected by the fractures (the back of the left leg and the so-called "broncone", i.e. the tree stump on the back of the right leg), most of them extremely thin. Images courtesy of A. Borri (BORRI et al, 2004).*

2. The fractures on the David

The small fractures we are sampling are in the lower part of the David, as it is shown in the images presented in Figure 1.Those cracks are known since the days of the statue translation from its original location, piazza della Signoria, to the Galleria dell'Accademia museum in year 1873. They were detected in the middle of nineteen century (BORRI et al, 2004) and their existence was one of the major issues under discussion while taking the decision to protect the statue in a museum. Since the discovery of this potential endagering condition of the Michelangelo's masterpiece, the hypothesis under discussion included both the bad quality of the marble (the lesions could have been original defects of the marble) or the occurrence of external actions (stress over the base of the statue originated by a subsiding basement, or the huge weight of the molding stuff used to produce a copy of the statue in XIX cent).

The recent investigations run in the framework of the last restoration of the statue (2004) gave some scientific evidence that similar small fractures could have been produced by a wrong inclination of the statue's pedestal (BORRI et al, 2004). This was assessed with a numerical structural analysis (using a FEM code), run over a digital 3D model of the statue.

3. Documenting the status with a digital model

As we have briefly introduced in Section 1, there are some constrains in the digital sampling of the status of the lesions:

- The width of the lesions is in most cases well below the sampling capabilities of modern 3D scanning devices.
- Visual analysis is usually helped by the colour discontinuities which are evident on most of those small fractures; therefore, performing also a sampling of the colour at high-resolution is a must.
- We should be able to monitor in time the evolution of the phenomena, therefore data gathered today should be compared to data gathered in future acquisitions. Since the surfaces sampled are not planar, it will not be easy to produce "orthographic" images, whose content could be metrically compared.
- No marks or visual guides could be left on the statue surface, to help framing the same regions in future acquisitions. Therefore, the alignment of data taken at different times should be performed only by taking into account the colour/shape features present in the data.

The approach planned to document the status of the fractures and, possibly, monitor the evolution in time is composed of the following components:

- Acquisition of a complete 3D model of the two regions under investigation, produced with the best sampling density and accuracy available.
- Acquisition of a photographic sampling, performed by a digital camera at very high resolution.
- Integration of the shape (scanned model) and colour (images) data into single, high-resolution digital model, which should support interactive visual inspection and analysis of the investigation equip (curators, scientist, art historians).

We detail in the following the technical choices and processes adopted to fulfill the goal above.

Figure 2: *Scanning the David.*

4. Acquisition of high resolution digital 3D models

The 3D scanning was performed by selecting one of the best system available on the market, the Breuckmann's smartSCAN-3D-HE. This system, based on fringe projection technique, is equipped with 2 CCD colour cameras, each with a resolution of 5 MPixel, allowing 3D surface scanning with highest resolution and accuracy. For further details see:

http://www.breuckmann.com/uploads/media/smartScan-HE_d_web_01.pdf .

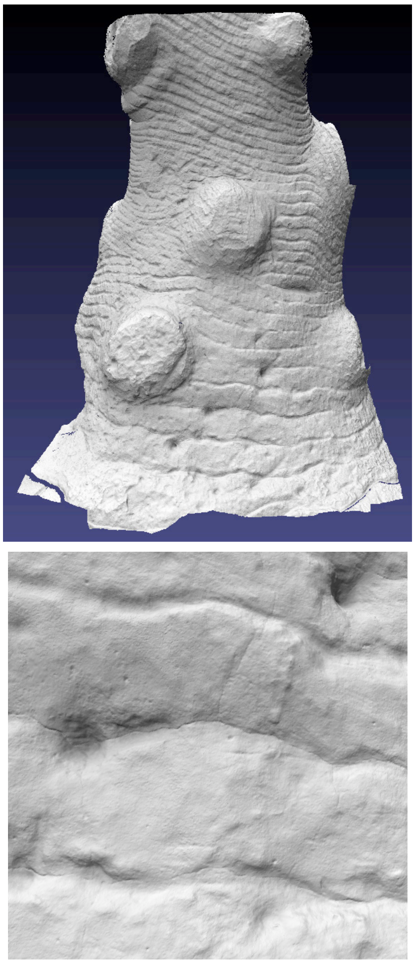

Figure 3: *First results of shape reconstruction from the 3D scanned shape data: the broncone 3D model is presented on the left, a zoom-in view is on the right.*

On-site scanning required minimal infrastructure (just a very simple scaffolding to rise the scanner at the height of the regions to be sampled, see Figure 2) and was very short in time: we were able to perform the acquisition in just 1.5 hours, including scanner setup time and calibration.

The acquisition was performed covering the entire region with a regular patchwork of shots. Each shot had a field of view with an image diagonal of 30 cm (approximately 23x19 centimeters), resulting in a spatial resolution of about 0.1 mm (inter-sampling distance). There was also a significant overlap between adjoining shots; this redundancy has two positive effects: it improves the quality of the subsequent range maps registration phase; it makes the sampling even denser than the nominal 0.1 mm inter-sampling density (due to the redundancy provided by the overlapping range maps).

Range maps were registered with the Breuckmann software, then filtered to remove some residual noise using MeshLab (CIGNONI et al., 2008) and finally merged with one of the reconstruction algorithm provided by MeshLab, the *"VCG Reconstruction"* filter based on discrete volumetric distance field.

The final master model has been reconstructed with a sampling resolution of 0.1 mm. Final reconstructed models are very dense: 128 M triangles in the case of the broncone (back of right leg), 57 M triangles for the left leg. An image of the 3D model obtained in presented in Figure 3.

5. Acquisition of a high resolution digital images

The photographic survey has been supervised and contributed by the Phototek of the Kunsthistorisches Institut in Florence (Max-Planck-Institut), in four hours. The goal was to acquire first, in a single shot, the entire region on each leg. Then, a small number of subregions were acquired by zoomin in those locations.

The camera used was an Hasselblad H3D, with a digital back supporting digital acquisition at 39 Mpixel. We estimate that each pixel in that global image is approximately sampling a surface parcel of size 0,12 mm.

The images have been processed using the Software Flexcolour v4.8.6 software. At acquisition time, a reference chart by GretagMacbeth (Colour Checker / Gray Scale card) has been used for the colour adjustment and to ebnable subsequent software colour calibration.

6. Integration of shape and colour data in a single 3D model

This phase has been performed by using ISTI-CNR proprietary technology that allows to align photos onto 3D models (FRANKEN et al. 2005; CORSINI et al. 2009) and to integrate and map those colour data on 3D meshes (CALLIERI et al. 2008).

The case of David's fracture opens some specific issues that have to be considered and solved. The first one is the extreme density of the data to be managed: even if we have a rather small region, we have both a huge shape model (e.g. the model of the broncone totalling 128M triangles) and huge images (39 Mpixels each). Second, since we have to represent very thin lesions, we require an extreme accuracy of the back-projection and mapping of the image data on top of the geometric model, in order to avoid typical artifacts like aliasing.

First, six of the acquired images have been aligned on the 3D model, using a new *image-to-3D mesh* alignment approach based on Mutual Information

(CORSINI et al. 2009). Then, the colour data were projected on the geometry following the weighted image blending approach proposed in (CALLIERI et al. 2008). The appearance information has been encoded with *colour-per-vertex* mode, which returns quite good results given the complexity and density of the 3D model (geometric sampling is approximately one vertex every one tenth of millimeter).

Figure 4: *Top: one of the images used for colour mapping. Center: a rendering of the coloured 3D model from a similar point of view. Bottom: a zoomed view on one of the cracks on the digital 3D model.*

Figure 4 shows one of the RGB images used to map colour on the mesh and two images rendered from the 3D model (an overall view and a zoomed-in view). The huge detail information encoded in the RGB images has been almost completely preserved in the 3D model. Moreover, the possibility navigate the 3D model (to change the light position and direction) and to perform measures (compute lenghts) enhances the potentials for the diagnostic work of the experts.

We are not aware of any other previous experience that tried to manage and integrate these amounts of data in a successful manner.

7. Preliminary results and conclusions

This paper presents the overall organization of the digital sampling and possible future monitoring of the visible status of the lesions on the lower part of the David statue. We have organized the sampling by performing an accurate digitization of both shape and colour of the selected regions; those high resolution data have been integrated in a single digital model, which can be interactively inspected and analyzed thanks to the progress of both 3D graphics GPUs and visualization solutions (multiresolution representation and visualization techniques).

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