

# A high-precision surface analysis of the roughness of Michelangelo's David

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## ABSTRACT

The knowledge of the shape of an artwork is an important element for its study and conservation. When dealing with a statue, roughness measurement is a very useful contribution to document its surface conditions, to assess either changes due to restoration intervention or surface decays due to wearing agents, and to monitor its time-evolution in terms of shape variations. In this work we present the preliminary results of the statistical analysis carried out on acquired data relative to six areas of the Michelangelo's David marble statue, representative of differently degraded surfaces. Determination of the roughness and its relative characteristic wavelength is shown.

**Keywords:** roughness, 3D model, micro-profilometer, scanning device.

## 1. INTRODUCTION

Optical techniques for shape measurements are non-invasive and thus they are particularly suitable for frail objects. Many of these are derived from industrial metrology, but the peculiarity of each artwork does not allow for a straightforward application. Measuring the roughness of an artwork by means of optical techniques, and in particular by microprofilometry, is becoming an useful tool for assessing the condition of the object surface. Roughness measurement deriving from a shape survey is thus a new application in the Cultural Heritage field, where scarce attention was paid to this kind of diagnostic. Roughness measurement of an artwork is important to document the surface condition, to assess either changes due to restoration intervention or surface decay due to wearing agents and to monitor the evolution with time in terms of shape variations.

The problem of measuring the roughness is complicated by the lack of rules defining it for the specific case of marble statues. Moreover, to assess the roughness a very accurate measurement of the surface is needed, with a height resolution in the microscopic range. This type of measure is often very difficult to perform on large statues, because it must be executed *in situ*. Generally speaking, the surface of an object can be described by three parameters, according to the spatial frequencies considered: *shape* (low frequencies), *waviness* (mid frequencies) and *roughness* (high frequencies). The three frequency ranges depend on the object dimensions: for instance, for an optical component, shape is related to the designed form, waviness is related to the deviation between projected and manufactured form, and roughness is the surface irregularity that causes light scattering.

In this work we present the preliminary results concerning statistical analysis carried out on data relative to roughness measurements on the Michelangelo's David marble statue. A three-dimensional survey was carried out by means of a laser scanning micro-profilometer. Data were acquired on six 4×5 cm<sup>2</sup> areas that are representative of the differently degraded surface. Measurements were realized before restoration started and will be repeated after the restoration intervention.

## 2. MEASURING THE ROUGHNESS

When describing the surface integrity of an artwork, an important parameter to deal with it is roughness. For instance, roughness measurements are the basis of many industrial quality controls. In this case, the roughness arises from the working process. Every surface has a certain amount of microscopic roughness, even if only at a molecular level, and the defects or features which contribute to it may be either random or regular (periodic).

The commonly used techniques for *in situ* roughness measurements are contact techniques, and they make use of stylus profilometers. The sample surface is investigated by means of a stylus or needle (often a diamond point) that is moved along the surface; its profile is then recorded. The system is usually calibrated with a known, flat surface: depth information is obtained by calculating the difference between sample and reference measurement. These profilometers have a very good quota resolution (up to nanometers), whereas lateral resolution depends on stylus diameter. The typical measured area extends to a few tens of millimeters with a measuring range of few millimeters.

Alternatively, for *in situ* roughness measurements optical instruments based on light scattering can be used. RMS roughness is then calculated on the illuminated area with a depth resolution up to 10 nm.

A variety of microscopes (scanning tunneling microscope (STM), atomic force microscope (AFM), laser force microscope (LFM), magnetic force microscope (MFM)) can also be employed for accurate roughness measurements, but only for laboratory applications.

A novel optical technique, the so-called conoscopic holography, has been recently developed. A laser beam, coupled to an optical microscope system, is split and then focused onto the test surface. Surface height is computed from intensity and phase information on the interference pattern: quota differences result in optical path differences that are seen as light and dark fringes on a video camera or diode array detection system. The surface shape is obtainable by mechanical, non-contact scanning. In the diagnostics of artworks the non-contact characteristic is a mandatory step: this requirement makes optical techniques particularly suitable for this purpose. Among them, conoscopic holography is probably the best compromise between good resolution and high data sampling.

### 3. SETTING UP THE INSTRUMENT

Roughness measurements on the Michelangelo's David, were realized by means of a conoscopic micro-profilometer system realized at INOA (National Institute for Applied Optics, Florence, see figure 2). The instrument is composed of a commercial Conoprobe mounted on two motorized high-precision linear stages. The probe (Conoprobe 1000 by Optimet) working principle is as follows: a light beam projected by a diode laser on the sample is both reflected and back scattered, and it impinges on a uniaxial birefrangent crystal placed between two circular polarizers (see Fig. 1). The ordinary and the extraordinary beams are then generated inside the crystal and produce an interference pattern [2 - 3]. The probe we used is equipped with a 50 mm lens which sets a quota resolution of nearly 1  $\mu\text{m}$  and a dynamic range of 8 mm at a stand-off distance about 40 mm. The overall accuracy is better than 6  $\mu\text{m}$ . The scanning device is composed by two motorized high-precision (0.1  $\mu\text{m}$ ) linear stages, that are perpendicularly assembled. The system allows measurement on a maximum area of about 300 $\times$ 300 mm<sup>2</sup>. The instrument has a maximum transversal resolution of 20  $\mu\text{m}$  with an acquisition speed ranging from 100 to 400 point/s, depending on the set spatial sampling frequency. The whole system is computer controlled.

The micro-profilometer allows measurements on surfaces with almost any reflectivity, with an incident angle up to 85°, that is to say, scanning at very close to grazing incidence is possible. Even the relieves of very small details, like holes 1 mm diameter less and 25:1 ratio between quota and diameter, are then possible [4-5]. Besides, the instrument is not sensitive to colour gradients; therefore it is particularly suitable for surveys of very detailed surfaces characterized by high chromatic contrast [6]. These characteristics, combined with co-linearity, allow the measuring of thin grooves and deep holes.

The instrument was modified for its use on a scaffold more than 7 m high, enclosing the David. Moreover, a special mechanical arm was realized to survey parts that were difficult to access otherwise (see fig.3 and 4). Due to its very fine resolution, the micro-profilometer body was tightened to the statue so to minimize vibrations and possible connected measurements errors, unavoidable when working on a scaffold like that. In order not to damage the statue, contact points were protected with felt.

Each investigated area is 4 $\times$ 5 cm<sup>2</sup> and was sampled with a 50  $\mu\text{m}$  step, corresponding to a range map of 801 $\times$ 1001 points. The images, obtained from the 3D model by means of digital filters, are shown in figures 8-10.

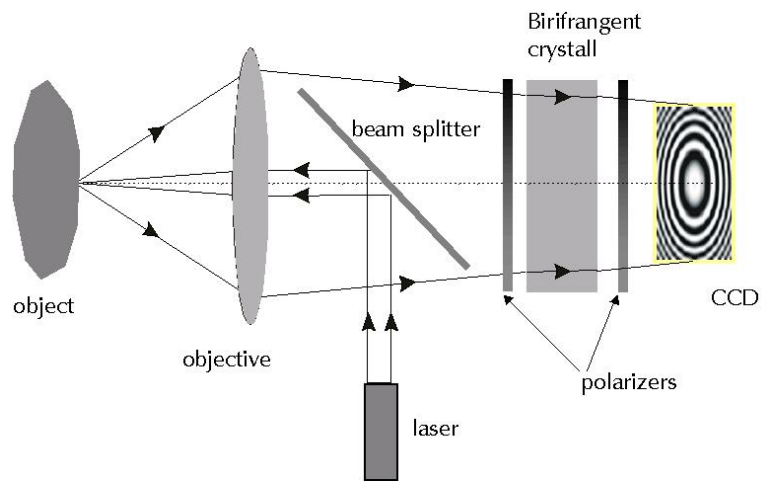


Figure 1 – The working principle of the conoscopic system

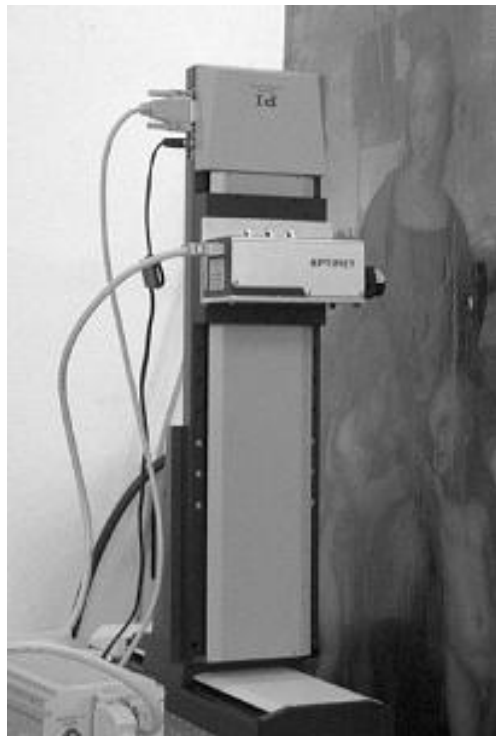


Figure 2 – The laser scanner micro-profilometer during a measurement on the panel painting “Madonna del Cardellino” by Raffaello.

#### 4. MEASUREMENT AND DATA ANALYSIS

The micro-profilometer scanning technique was applied on various panel paintings and statues, with different instrument configurations purposely studied in order to put in evidence details which are not visible at sight and often not detectable with other techniques. The measurement results allow to reveal painting detachments, deformations of the materials and also the roughness of the surface.

We report here an example of this last kind of application, the study of roughness of a (remarkably well-known) marble statue: the Michelangelo's David (see figure 3a and 3b). The statue exposed at the *Museo dell'Accademia* Florence is currently under restoration.



Figure 3a – The Michelangelo's David.



Figure 3b – The set-up installed for the measurement.



Figure 4a – The measurement of the sling



Figure 4b – The measurement of the left foot finger.

The restoration project [7] has two objectives: first of all studying and then monitoring the “health” of the sculpture that has not been touched since 1873 when it was moved to the Accademia from Piazza della Signoria; the second goal is doing the whole cleaning that the statue needs, darkened and stained as it is by the accumulation of dirt. Its surface is seriously damaged due to a first incident occurred in 1512 when the base of the statue was struck, later in 1527 the left arm was broken into pieces during an uprising in *Piazza della Signoria*. Between 1808 and 1815 an “encausto” patina was applied to the David in order to protect it from atmospheric elements. In 1843 the statue surface was cleaned with a solution containing 50 % chloric acid, and finally in 1873, when David was moved from *Piazza della Signoria* to the

*Galleria dell'Accademia*, the statue suffered from instability and numerous cracks occurred.

In light of these facts the necessity of intervention on David with specific maintenance operation became mandatory. The analysis of the roughness certainly allows to understand how much those previous interventions of restoration or the various accidents affected the statue had compromised the marble surface of this masterpiece. As it was already explained, the instrument is very sensitive to vibrations induced both by the instrument motion and by the environment, so during the measurement, it is necessary to avoid vibrations. We tried this by securing the instrument to the statue in order to damp possible vibrations. This has been a tough point in the measurement, since it is clearly not possible to fix something onto the David. We realized the contact, thus, with suitable materials preventing any damage to the artwork itself. The instrument was then “linked” to the statue by using properly felts and a synthetic tape, thus avoiding surface scratches. The system at work during the measurements is shown in figure 4a and 4b.

A further problem has been that the system acquires only very small areas, because of the long measurement time required for scanning. Then it has been necessary to choose accurately the areas to be investigated in order to obtain a sampling of all the possible situations present on the artwork. We proceeded indeed in this choice according with the indications by the scientific committee for the David project.

The measurement was carried out in October 2002, and six areas 4×5 cm<sup>2</sup> large were investigated, and with a high space frequency sampling (50 μm). The number of acquired points is 801 in x direction and 1001 in y direction. The software of acquisition (developed at INOA) allows to register not only the z profile of the surface, but also the x and y profiles as it is possible to see in the figure 5 in which is shown an example of acquired area in color scale where different color means points that more or less near to the reference plane. These acquisitions were then elaborated by software tools in order to reveal very small particulars such as signs of working or corrosions.

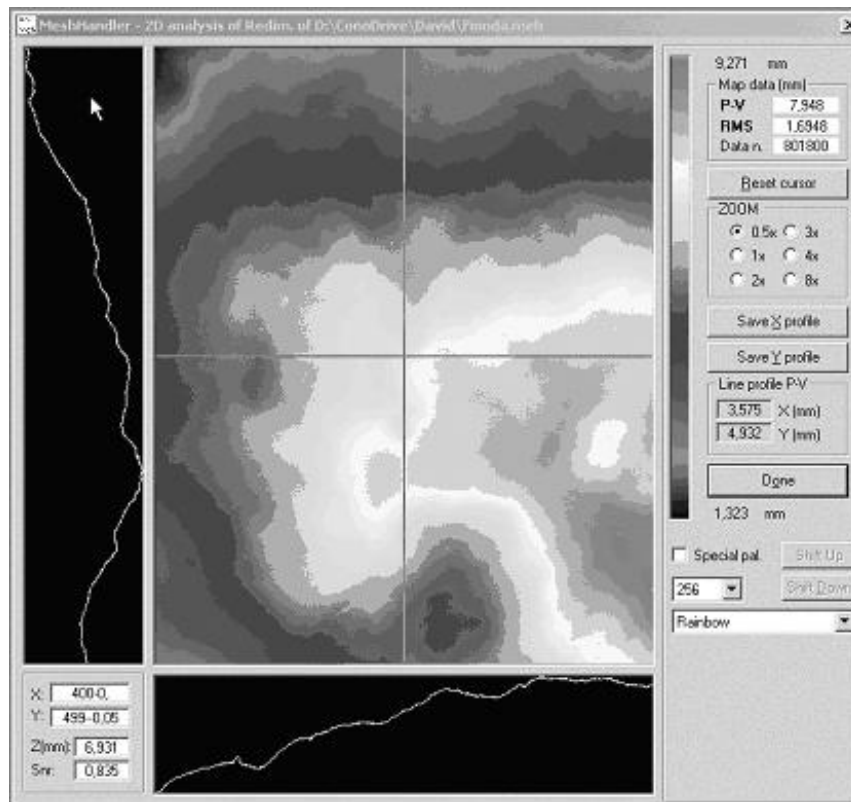


Figure 5 – The acquisition software user interface

Roughness can be defined in terms of deviations from a mean surface level and can be described by means of the RMS (Root Mean Square) value around it ( $R_q$ ) and the wavelength ( $\lambda_q$ ).

Assuming an horizontal surface ( $\bar{z}$ ), roughness is then given by

$$R_q = \sqrt{\frac{1}{N} \sum_{i=1}^N (z_i - \bar{z})^2}$$

where  $z_i$  is the measured quota for the  $i$  point and  $N$  the number of points.  
 Defining  $\Delta q$  as

$$\Delta q = \sqrt{\frac{1}{N} \sum_{i=1}^N \left( \frac{\Delta z_i}{\Delta y_i} \right)^2}$$

where  $\Delta y_i$  the spacing between adjacent points, the wavelength  $\lambda_q$  is

$$\lambda_q = 2\pi \frac{R_q}{\Delta q}$$

Therefore  $R_q$  is a measure of the roughness amplitude,  $\lambda_q$  is a measure of its characteristic length.

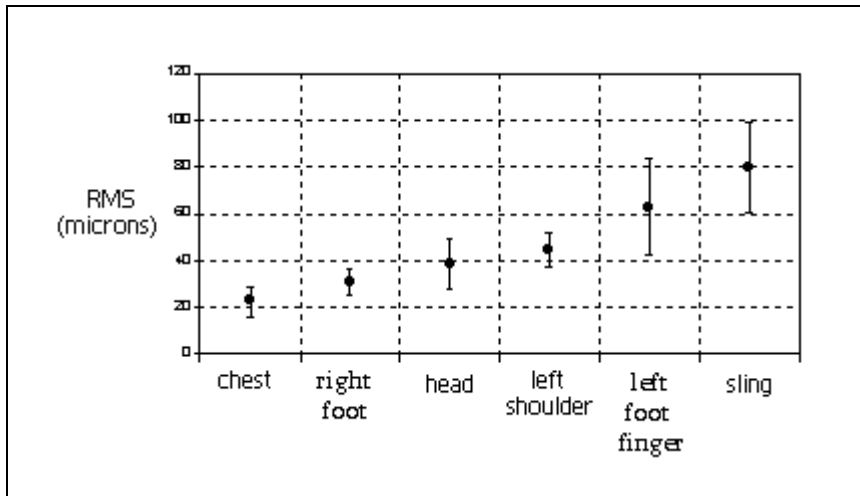


Figure 6 – The RMS calculated results.

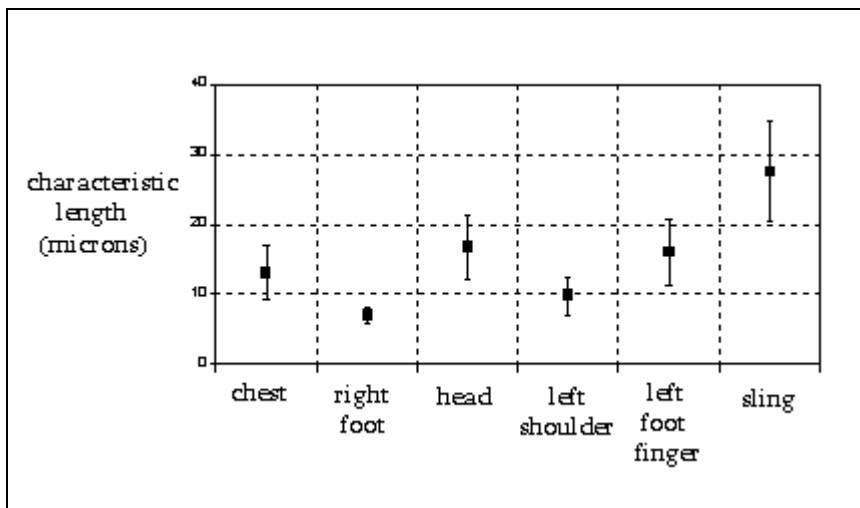


Figure 7 – The calculated characteristic length  $\lambda$



Figure 8a – The left shoulder

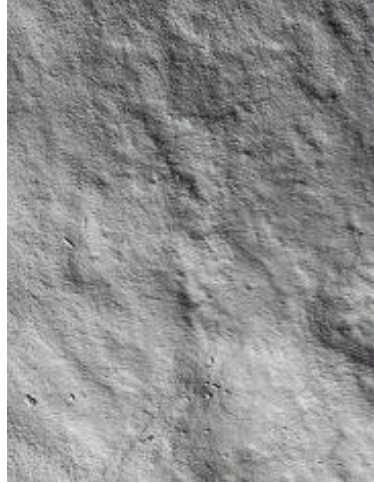


Figure 8b – The sling

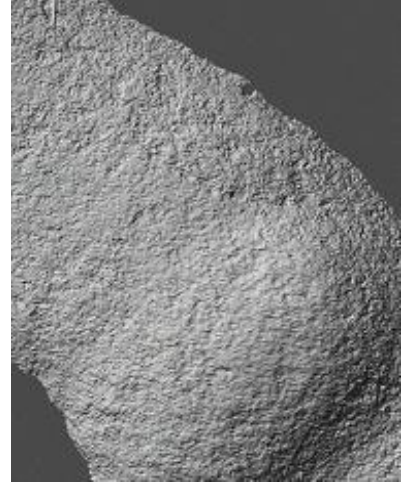


Figure 8c – The left foot finger

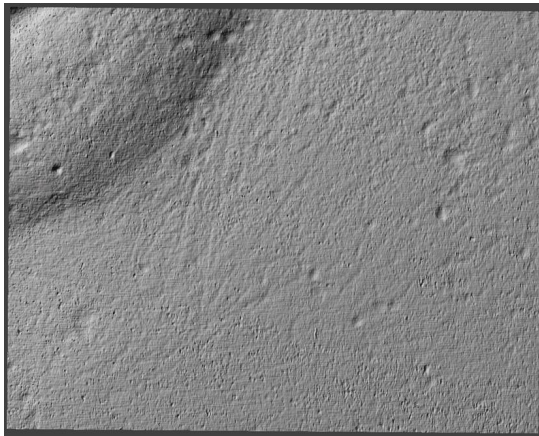


Figure 9a – The chest

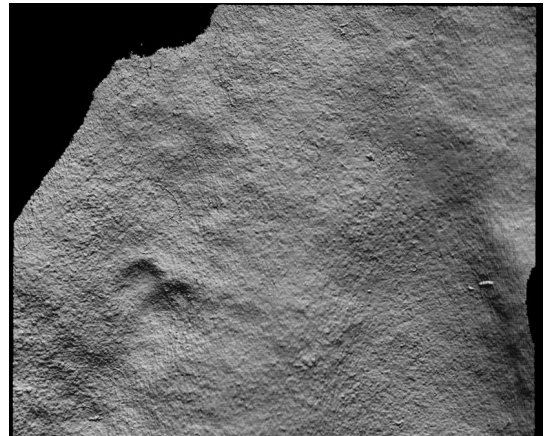


Figure 9b – The head

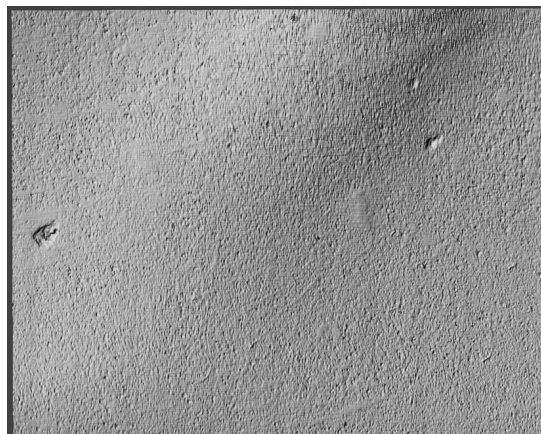


Figure 10 – The right foot

We selected 1x1 cm<sup>2</sup> “nearly flat” areas, meaning that we chose areas where there was not abrupt shape variation within them. Moreover, in order to correct for any minor shape variation (waviness) within the sample area, for each acquired line a parabolic fitting curve was computed and subtracted from the data. The RMS roughness value was computed on each acquired line. The mean value and the standard deviation were then calculated for each sample area. The results are shown in table 1 and plotted in figure 3, together with the error bars representing the measurement variability range.

A more detailed study of the roughness will be carried out by varying the dimensions of the sub-area under investigation, and by varying the investigated area itself.

Roughness measurements of marble statues is quite an unexplored field, due to the absence of rules or case studies one could use as references.

In Table 1 the results of measuring the roughness (RMS) are shown for the six points measured. The same results are graphed in figure 6 and in figure 7. In figure 6 are the roughness values whereas in figure 7 the calculated values for the characteristic length are shown. These values are obtained from the analysis of an area of 1 cm<sup>2</sup>, arbitrarily chosen as representative of the whole sampled area.

Area	Roughness RMS (microns)
Head	38.61
Shoulder	44.64
Sling	79.89
Chest	22.61
Right foot	30.89
Left foot finger	62.74

Table 1- The calculated roughness RMS for the six investigated areas.

By applying suitable filters (*embossing*) to the acquired 3D maps of the surface, a raking light illumination is simulated. This qualitative approach shows the corrosion of the investigated areas: working signs, scratches, chisel marks and also the possible signs left during the restoration. In figure 8, 9 and 10 all the elaborated images related to the six analyzed areas are reported. As it can be seen in these figures all these areas display different situations regarding roughness, waviness and different stages of damage.

## 5. CONCLUSION

In this paper we reported the roughness measurement of the David by Michelangelo, carried out by a system assembled by the Art Diagnostic Group of INOA. This preliminary measurement stresses the complex situation of the marble surface due to previous restoration interventions and to pollutant. At the end of the present restoration the measurements will be repeated and the two situations will be compared. These measurements will be used to analyze how the cleaning process has affects the surface of the statue, in the selected areas. Obviously, our hope is to measure a very small difference, or better, to measure a zero (difference within the instrument resolution).

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