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MORPHOMETRIC ANALYSIS OF ENGRAVINGS FROM PHOTOGRAMMETRIC POINT CLOUD DATA

1. Introduction

Current point data capture technologies allow measuring three-dimensional coordinates of myriads of points in a very short time. Usually referred to as point clouds, this kind of data can be captured by different methods (Remondino, El-Hakim 2006), the most frequent being laser scanning and digital photogrammetry.

Both strengths and flaws can be found in these two major methods, which should be regarded as complementary rather than alternative. The relevant issue is that, either isolated or in combination, they allow for a very high resolution in point clouds, ranging from a few millimetres (for a sensor-to-object distance of about 50 m) to some tens of microns (for object distances below one meter).

Owing to such a high resolution, very detailed Digital Surface Models (DSMs) can be generated from these data. Should accuracy be achieved to a similar level, resulting DSMs would not only be detailed but also precise, thus providing the users with a very exact geometric representation of the object surface shape.

Applications of photogrammetry in heritage documentation can be dated back to the origins of this science: Albrecht Meydenbauer is regarded to be both one of its founders and a pioneer in this kind of applications (Albertz 2001). Among these, recording rock art objects like pictographs and petroglyphs is especially remarkable, because under no circumstances should such evidence be touched in any way, and photogrammetric measures are performed in a non-contact manner.

One of the first rock art photogrammetric surveys was carried out in 1957 in Altamira Cave (Spain) to build a partial replica of the cave ceiling area containing the most relevant pictographs (Belzner 1959; Pietsch 1963). Another early work was the recording of prehistoric carvings at Stonehenge (Atkinson 1968). A second survey of Altamira Cave in 1977 (Llanos Viña, García-Lázaro 1983) and Scogings' works (1978) can be cited too.

Following this line, more recent articles (e.g. Chandler, Fryer, Kniest 2005) report the use of photogrammetry to produce point-cloud based DSMs of petroglyphs. Most of these works emphasize the value of this kind of data in documentation tasks, but less attention has been paid to analysis.

In this paper, the authors describe their first steps in the analysis of engraved surfaces from a geometric point of view. In this perspective, engravings can be thought as abrupt alterations of the original surface shape, possibly combined with further modifications due to erosion and anthropic action. A numeric characterisation of surface alterations is envisioned to be the basis for an objective description, identification and classification of engravings.

Changes in the shape of a surface can be evaluated using morphometry, a science which is indeed defined as "the measurement of shape" (Pidwirny 2008). In this work, morphometry is understood much in the sense of what Evans (1972, 18) called "general geomorphometry": «the measurement and analysis of those characteristics of landform which are applicable to any continuous rough surface».

General geomorphometry attempts to characterise terrain surfaces by assigning every point on them to a class of topographic features: pits, peaks, channels, ridges, passes and planes. These features may be described unambiguously (Wood 1996) in terms of the so called "morphometric parameters" (slope, curvatures and the like), most of them computed from the derivatives of elevation. The foundations for this characterisation are rooted in the mathematical analysis of surface geometrical forms, started in 19th century by Gauss in his *Disquisitiones generales circa area superficies curvas* (Shary, Sharaya, Mitusov 2002).

Analogues of topographic features can be conceived on the engraved surfaces as a result of the carving action. Their definitions and descriptions are doubtless a task for archaeologists, historians and other rock art experts, but these "carving features" could also be described in terms of morphometric parameters. In doing so, the spatial distribution of, say, surface slopes or curvatures would help in their identification. Thus, the starting point in the proposed analysis is mapping the distribution of some morphometric parameters on engraved surfaces, in the expectation of the hypothesised carving features being highlighted this way.

Morphometric analysis of topographic surfaces is usually performed on DEMs rather than on direct terrain measures. In a similar fashion, the analysis proposed in this work is to be carried out on digital models of the engraved surfaces. A test case is presented here, with the DSM being interpolated from photogrammetric point cloud data.

2. Test object

A simple case study was desirable for the first experiments: not too big the object, not too small the carvings, not too complicated the surface. Easiness to access the object was also an issue, because archaeological sites are usually highly restricted and a lot of permissions must be requested prior to any work. So a simple, free-to-visit object was searched for, the choice having been a 60×60 cm epigraph engraved on the base plinth of a granite votive cross outside the church of a small village (Santo Domingo de las Posadas, Ávila, Spain) (Fig. 1).

Fig. 1 – View of the votive cross showing the epigraph on the base plinth and the Kiev 88 camera used in the survey.

The epigraph registers the name of the offering person and the year the cross was erected (1673). The order of magnitude of the characters is roughly 5-10 mm in width, 2 mm in depth and some centimetres in length, so they are quite similar in size and shape to linear carvings in many petroglyphs. Furthermore, the cross is more than 300 years old, the engraved surface having been eroded to some extent. So, in a geometric sense, this object is similar to many of the ones to be dealt with in rock art applications, and methods doing well with this epigraph can be expected to provide a feasible starting point in this research.

3. Photogrammetric survey and DSM generation

Not many photogrammetric innovations are to be found in this paper, the applied method being not too different from what Chandler, Brian, Fryer (2007, 12) call «the humble stereopair». Doubtless, sophisticated photogrammetric data capture methods and equipment are desirable to achieve the best results in whatever the applications, but in this research the stress is on products derived from photogrammetric data, rather than on photogrammetry itself.

3.1 *Photographic equipment*

A reliable morphometric analysis of carvings requires their shape to be known in detail, so resolution is the main concern related to data capture in this work. In a photogrammetric context this is to be understood as angular resolution and is not only dependent on image resolving power but also on camera focal lens; the longer, the better. For a good trade-off between resolution and object coverage per image, long focal lenses are better used with large format cameras, a medium-format and normal-angle camera being a reasonable option for this work.

Medium-format high-resolution digital cameras are rather expensive, not to be afforded in the very initial steps of this research, so the analogue option was considered instead. A Kiev 88 camera mounting an 80 mm f/2.8 Volna-3 lens was used and the pictures were digitised later in a photogrammetric scanner. Frame size of Kiev 88 is 56×56 mm and scanning pixel size was 8 microns, so the resulting digital images were about 46 mega pixels in size, a resolution similar to the most expensive digital cameras. Not everything is good in this choice, however: medium size analogue photographs are prone to film lack of flatness and shrinkage, what is against accuracy of photogrammetric results.

3.2 *Camera calibration*

Kiev 88 is a non-metric camera, so neither its internal orientation parameters are known nor fiducial marks are available. The first lack is usually overcome by means of a self-calibrating block adjustment, whilst the second can be circumvented by using the image corners, provided that coordinates of these points are determined such that the principal point of all the images can be referred to a common, fixed to the camera body reference system. When digital cameras are used, an image coordinate system can be built up from pixel size and number of pixels, taking for granted they are rectangular. Analogue cameras, however, require their frame corners to be measured.

Direct measuring of the camera frame corner coordinates requires special devices, not available to the authors. An indirect approach was used, measuring image corner coordinates of a certain number of Kiev camera negatives in a Wild Aviolith analytical plotter used as a monocomparator and then averaging the results.

Because each negative is placed in a different position on the plate carrier, comparator coordinates of image corners cannot themselves be averaged, so distances and angles among them were considered instead. These magnitudes, derived from measured coordinates, can be averaged and used to build a figure which may be regarded as an estimate of the camera frame size and shape.

Fig. 2 – The three Kiev 88 pictures of the epigraph.

The corners of this figure may be coordinated in any convenient but otherwise arbitrary reference system, and used as fiducial marks in further jobs.

Interior orientation was modelled with five parameters, namely the principal distance c_k; the principal point coordinates x_p, y_p; and the first and second coefficients of the radial-symmetric distortion polynomial, k_1 and k_2. No further distortion parameters are usually accounted for when using consumer grade cameras, especially if cone is normal-angle (Fraser n.d.). Values of these parameters at working focus setting (900 mm) were known from previous calibration jobs.

3.3 *Photogrammetric data capture*

Three images were taken roughly perpendicular to the engraved surface, configuring two 60% overlapping normal case stereopairs. Kodak 160 VC colour negative film was used for the photographs. Lens aperture setting was f/22, to achieve the maximum depth of field, and exposure time was set to 1 second.

Photo scale of the photographs was 1:10, each image pixel covering roughly 80×80 microns in object space, so an average 5-10 mm groove cross section is about 60-120 image pixels in width. Base and distance-to-object in the stereopairs were 250 mm and 900 mm in length respectively. Thus base-to-distance ratio was greater than 1:4, a reasonable value for DSM extraction according to Chandler, Brian, Fryer (2007).

No control points were measured, but a ruler was included in the scene to scale the block. In addition, six points were targeted on the object for an easy identification and precise pointing, so that they could be used in the initial steps of the orientation adjustment (Fig. 2).

Upon image development, a Delta GeoSystems photogrammetric scanner was used to digitise the photographic negatives. Geometric accuracy of this scanner is ± 2 microns rms and pixel size was set to 8 microns as aforementioned.

3.4 *Photogrammetric data adjustment*

Two software applications were used in the photogrammetric process, Digi 3D version 2005.0.25 (©2000-2005 by Manuel Quirós & José A. Martínez-Torres) and Taller Fotogramétrico (©2002–2008, Francisco J. García-Lázaro). The image coordinates of the six targeted points, the extreme marks of the ruler and seventy-two additional natural points were measured on the photographs with Digi 3D. Then, a bundle adjustment was run by means of Taller Fotogramétrico program. The a posteriori standard deviation was 0.008 (dimensionless) and the average accuracy of object coordinates was about 0.14 mm in XY and 0.50 mm in Z, as shown in Tab. 1.

Stereoscopic inspection revealed residual vertical parallaxes up to 30 microns in some parts of the models, larger than expected considering the adjustment standard deviation. These very high values are probably due to film shrinkage and lack of flatness during the exposure, and were of concern in the automatic point measuring process.

3.5 *Automatic point-cloud measurement*

Digi 3D uses cross-correlation to identify conjugate points in a stereopair. This method requires setting up some parameters for a proper matching. Parameters may vary slightly from one program to another, but are conceptually similar in whatever the software, and always include the minimum allowable correlation coefficient, the size of correlation windows, an approximation to object space Z's (either range or average) and the maximum displacements of a candidate point from its initial position in both x and y directions, defining the size of the search window and corresponding to slope and y-parallax tolerances respectively.

Tab. 2 shows the parameters used in Digi3D, together with their settings in this work. To be noticed is the high tolerance setting in y-paralax tolerance (30 microns), in accordance with the high residual values detected when inspecting the stereoscopic models.

The distance between measured points was set to 0.5 mm in object space, what is roughly equivalent to 6 pixels in image space, twice the minimum of three pixels usually recommended. Tab. 3 shows the matching process results.

Estimator	mX (mm)	mY (mm)	mZ (mm)	mP (mm)
Average	0.14	0.13	0.50	0.53
90 percentile	0.20	0.18	0.70	0.76

Tab. 1 – Object space points accuracy after block adjustment.

Parameter	Meaning	Value
Correlation tolerance	Minimum allowable value of correlation coefficient	0.40
Correlation window size	Size of the window centred on sampled and candidate points to compute grey-level correlation in a pixel to pixel basis (in pixels)	15×15
Z range	Minimum and maximum admissible Z (in object space coordinate units)	0-100
Slope tolerance	Maximum Z difference between two consecutive matched points (in sampling steps)	0.40
y-paralax tolerance	Maximum distance between a candidate image point and the epipolar line as estimated from its conjugate (in microns)	30

Tab. 2 – Digi 3D cross-correlation image matching parameters and their settings.

Performance	Left pair	Right pair	Total
Number of measured points	479591	554322	1033913
Points per correlation factor:			
1.00 > r ≥ 0.60	57 %	60 %	58 %
0.60 > r ≥ 0.40	43 %	40 %	42 %

Tab. 3 – Results of the image matching process.

3.6 *DSM generation from the point cloud*

Morphometric analysis operations are usually carried out on raster DSMs, which can be conceived as a regular two dimensional array of heights (a grid), sampled above some datum, that describes a surface (Wood 1996). In most DSM generation workflows a TIN is first built out of the measured points and then used to interpolate a grid. This is of course the proper method when all or most of the "very important points" (VIP) defining the surface are measured. However, automatic image matching methods do not search for VIPs, but rather perform a blind sampling of the images at the specified resolution. In this case, triangulation is not so clearly justified, and may be avoided by interpolating the grid DSM directly from the point cloud.

A simple option is the use of spatial moving averages. These may be either exact interpolators, honouring all the data points, or smoothing interpolators, allowing for slight modifications in the data points Z coordinates, based on neighbour values. The later exploit the high positive spatial autocorrelation usually existing among close values of this coordinate.

Some authors, for instance Evans (1998), consider questionable the use of exact interpolators for DSM generation because no data are error-free and thus some smoothing is appropriate. Despite this issue, exact interpolators were the choice in this work because smoothing is applied to the surfaces during the analysis process.

Inverse distance weighting interpolation (IDW) was used to generate a 0.25×0.25 mm cell size grid DSM, half the sampling step used in image match-

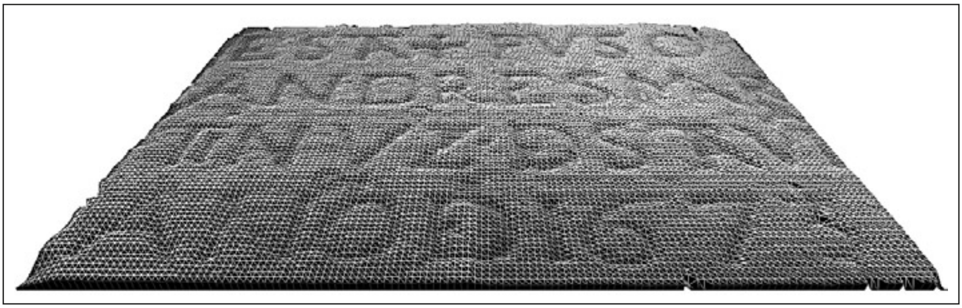

Fig. 3 – Perspective view of the epigraph DSM grid.

ing. A 2 mm radius circular roving window centred on each grid point was used. IDW is a very straightforward exact interpolation method and results in a good estimate of a surface, provided that measured points are sampled very densely (Hengl, Gruber, Shrestha 2003, 7), such that every interpolated point is close to several observations. This is the case in this work where the sampling step has been 0.5 mm and grid size is 0.25 mm as shown above, so there are four observations in the immediate neighbourhood of each grid point and about 50 observations within the 2 mm radius roving window.

Graphic outputs of the epigraph digital surface model are shown in Fig. 3 and Fig. 4. The first offers a perspective view of the gridded surface, downgraded to a 5 mm resolution for visualisation, and the second displays a shaded relief representation.

4. Morphometric analysis

Among the existing morphometric parameters, slope and mean curvature were the choice for the first experiences, and models of their distribution were generated from the epigraph DSM. These so-called derived models are computed from the derivatives of the DSM variable with respect to the axes of the grid reference system. Thus, models of morphometric parameters are related to variations in the surface shape.

Morphometric parameters are continuously varying over the real surface and what is actually measured, whatever the way they are computed, is their average over a certain area, the size of which defines the scale of the analysis (Albani *et al.* 2004), where "scale" is to be understood as the extent of surface intervening in parameter computation and the size of involved surface features.

Morphometric models derived from a DSM are generated by centring a roving window on each of the grid points in turn and adjusting a function to

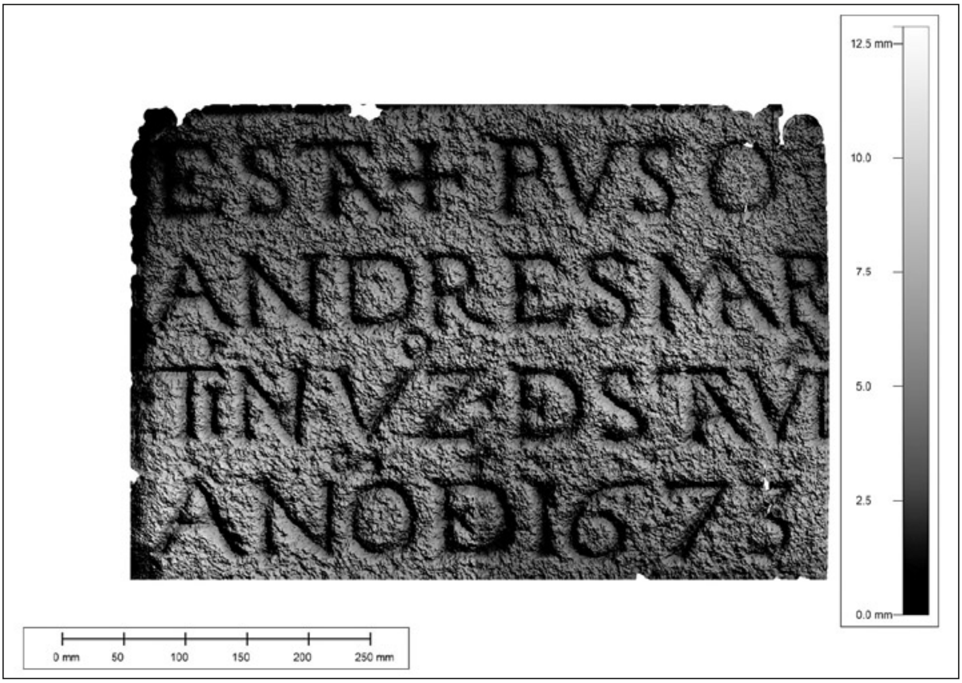

Fig. 4 – Shaded relief visualisation of the epigraph DSM.

the grid points contained in the window. Morphometric parameters are then computed from the derivatives of the function and their values are assigned to the grid point where the window is centred. In this approach, the extent of surface intervening in parameter computation is that of the window, so window size defines the analysis scale and is to be chosen carefully.

Different functions can be used, one of the most frequent being the biquadratic polynomial (Evans 1980), which is regarded to provide the most precise estimate of the derived models in the presence of measuring errors in the original data (Florinsky 1998).

The freely distributed program LandSerf version 2.2 (© Joseph Wood 1996-2005) was used in the analysis. Albeit designed for geomorphometric purposes, this software could be applied because the engraved surface was originally roughly a plane, so a family of "natural" reference systems exists (the set of reference systems having their Z axis perpendicular to the surface) whose axes can be used to compute the required surface derivatives with respect to them. The Evans' biquadratic polynomial function is used in LandSerf program to compute morphometric parameters.

One of the main advantages of this program is the possibility of using square windows of any size to adjust the function, provided their side length corresponds to an odd number of grid points. The larger the window size, the stronger the smoothing applied to the DSM. High frequency noise, for instance measuring random errors and surface grain, can be removed in this way. Those morphometric features which are small compared to the window are filtered out, too. This enables surface analysis to be carried out at multiple scales.

Several window sizes were tried in this work to generate the different derived models, ranging from 11×11 grid points to 55×55 grid points (2.50×2.50 mm to 13.50×13.50 mm). The aim was to find the best sizes to reveal the hypothesised carving features. The results of these experiences are described and shown below.

4.1 *Slope models*

Slope is computed from the first order derivatives of the DSM variable, and quantifies its rate of change in the steepest descent direction. Fig. 5 shows four partial slope models of the engraved surface, generated with different window sizes. As window size increases, a more generalized model results, filtering out minor slopes due to surface grain and measurement errors and highlighting what could be called the "hillsides" or "slopes" of the grooves. However, generalisation may be excessive if window size is too large, such surface features being blurred.

Mean curvature at a surface point can be informally defined as the average curvature of all the surface normal sections containing that point. Curvatures are computed from the second order derivatives of the DSM variable and quantify the "rate of change of the rate of change" of the variable; so, curvature models can help to identify changes in slope. In linear carvings, convex slope changes happen at groove borders, where the original surface and the carved surface meet, and concave slope changes occur at the bottom-line, where two carved slopes meet.

Again up to a limit (Fig. 6), the larger the window size used in generating curvature models, the more surface grain and measurement noise are filtered out highlighting carved features. This time it is the grooves bottom-lines (the "talwegs") which are clearly revealed by high negative values on the mean curvature model, when a proper window size is used in its generation. Small windows generate noisy results, whilst too large windows produce blurred results, the inferred bottom lines being too thick.

4.2 *Further processing using GIS tools*

Standard GIS tools like Map Algebra functions (Tomlin 1990) can be used to extract the morphometric carving features identified by the preceding

Fig. 5 – Slope models generated with different window sizes: (A) 11 grid points, (B) 25 grid points, (C) 35 grid points (D) 55 grid point.

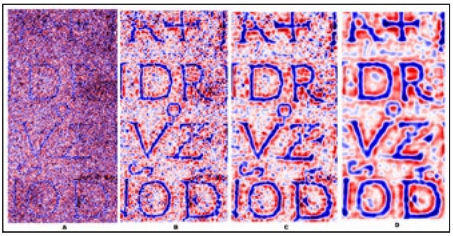

Fig. 6 – Mean curvature models generated with different window sizes: (A) 11 grid points, (B) 25 grid points, (C) 35 grid points (D) 55 grid points.

method. To do this, the range of parameter values characterising a particular surface feature type must be established. Then, a simple local rating can be used to reclassify the values of the derived surfaces such that the desired features are extracted. The 35×35 grid-points window was judged to provide the best results in revealing carving features, so this process was carried out over the models derived with this window size.

Parameter values were sampled on the derived models to determine the ranges of values characterising groove hillsides on the slope model and talwegs on the mean curvature model. The estimated ranges were 10% and greater for slopes, and -0.40 mm^{-1} and lower for curvatures. A local rating was then applied to derived models by setting the values comprised within these ranges to 1 and every other value to void, to extract binary rasters of the corresponding surface features. LandSerf tools for raster values transformation were used in these operations. Fig. 7 and Fig. 8 show the binary rasters of the inferred hillside slopes and the talwegs of the engraved characters.

4.3 *Surface profiles and cross-sections*

Other morphometric approaches can be adopted which could equally benefit of DSM based measuring methods. For instance, Urbani (1998) describes a morphometric characterisation of the linear parts of petroglyphs very different from the one presented here. It is based on several parameters (symmetry, sharpness, V-shape and flatness index) computed from measures taken from a series of groove cross-sections.

In Urbani's work these last are determined by two different methods, both object contacting, something to be avoided when dealing with heritage objects. However, cross sections can be easily obtained from DSM's, allowing an unrestricted use of Urbani's method. The sections can be plotted to perform whatever the desired measures or they can be displayed and referenced in a

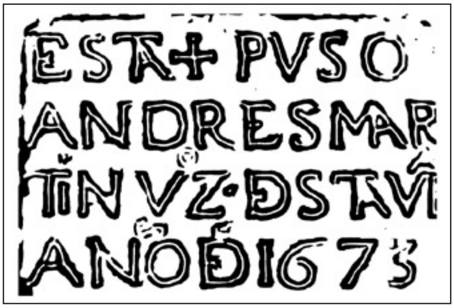

Fig. 7 – Binary raster of grid cells having slope values greater than 10% in the slope model generated with the 35×35 grid points window, corresponding to carving hillside slopes.

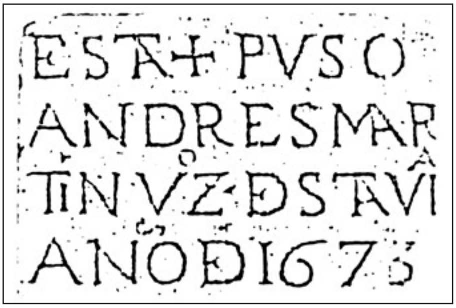

Fig. 8 – Binary raster of grid cells having curvature values lower than -0 -40 mm^{-1} in the mean curvature model generated with the 35×35 grid points window, corresponding to carving talwegs.

CAD environment, where more accurate measures can be performed. Fig. 9 shows a surface section across the first letter N appearing in the text.

5. Discussion

Morphometry seems to offer useful tools for the analysis of engraved surfaces. Figs. 5 and 6 demonstrate how displaying the spatial distribution of the selected morphometric parameters leads to an enhanced view of the epigraph characters. In addition, some possible morphometric features are suggested in doing so, which can be numerically identified and extracted by further processing of the derived models using standard GIS functions, as shown in Figs. 7 and 8.

Nevertheless, an easy straightforward extension of geomorphometric methods to the analysis of engraved surfaces should not be concluded to be the general rule. The basic geomorphometric magnitude is elevation, which is measured along vertical lines in the direction of the gravitational field of forces, intimately related to most geomorphogenetic processes indeed. Vertical lines can be considered parallel across wide land extensions, because the angle between two verticals separated 100 km is about 1 gon. So, changes in elevation can be expressed in terms of the surface derivatives with respect to three perpendicular axes, one of them being parallel to the vertical direction.

The equivalent of elevation for engraved surfaces in engraving morphogenesis is carving depth, measured along a perpendicular to the original surface. If this is roughly a plane as in our example, the reference system can be chosen such that its Z axis is normal to the surface, so variations in depth are just variations in Z and can be again expressed in term of the surface derivatives with respect to the reference system axes.

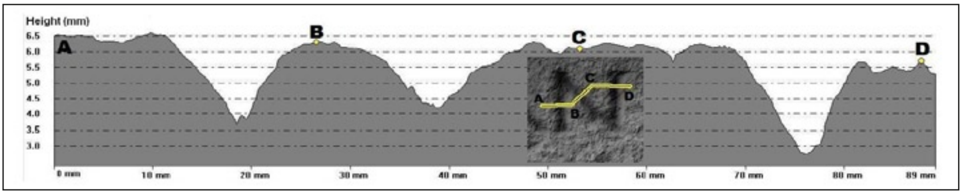

Fig. 9 – A surface section across one of the engraved characters (the first letter N in the epigraph).

However, as far as the original surface is not a plane depth measuring directions will not be parallel and no reference system will exist such that the surface derivatives with respect to its axes can fully account for depth variations. Even if the reference system XY plane is as close as possible adapted to the surface, slope will be likely an underestimation of the carving depth rate of change, and carving hillsides identification in the manner presented here might fail when the original surface is highly curved.

Fortunately, mean curvature is a reference system independent parameter (Shary 1995) and no similar drawbacks affect talweg extraction. So, a sound study of the relationship between the reference system and the diverse morphometric parameters will be required. The scale problem and the choice of the interpolation method are other morphometric questions to address in the research.

Some photogrammetric questions must be considered too. A medium format film camera was used in combination with a scanner for data capturing in this work. This was the most direct way of getting the required resolution, because both resources were already available. However, photographs taken with such cameras may lack dimensional stability and lead to poor accuracy in the results. In addition, simpler data capture approaches should be convenient to address the potential end-users of the methodology under research, likely archaeologists, historians and other rock art or epigraphy related scholars rather than practitioners of photogrammetry.

The sensor of a digital camera is more stable than film, so accuracy could be improved by using cameras of this kind, provided the resolution is enough and the focus setting can be fixed. Furthermore, these devices simplify the data capture equipment, because they require no scanner. A full frame SLR digital camera offers a simple solution and probably the best trade off between cost and accuracy.

6. Conclusions

Simple photogrammetric methods can produce high resolution digital models of engraved surfaces. By processing models of this kind with standard geomorphometric software, some structural carving features have been identified and extracted. These results suggest the possibility of developing a specific morphometric analysis methodology for engravings and encourage further research to extend rock art and epigraphy applications of digital surface models beyond their current use in documentation, visualisation and virtual reality creations.

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ABSTRACT

Simple photogrammetric data capture methods and equipment are able to measure accurate dense point clouds and detailed high geometric quality Digital Surface Models (DSMs) can be generated out of them. These products are frequently applied to the recording of rock art. However, their potential is not just limited to documentation and their use can be extended to perform analytic tasks. This paper describes the authors' first experiments in the morphometric analysis of an engraved surface (an epigraph), based on a DSM generated from photogrammetric data. Slope and curvature models were derived from this DSM and used to identify and extract some structural features of the carvings, much in the same way as topographic landscape features can be identified on a terrain DEM.