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Morphological Analysis of Shape Semantics from Curvature-based Signatures

The Case Study of the Columns of Saint-Michel de Cuxa

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***Abstract*— Over the past few years, advancements in the field of 3D digitizing has increased the fidelity of geometric models. So far and despite of this acuity enhancement, a gap remains between the growth of collected data and its uses as vehicle of knowledge. New challenges have emerged to handle massive content of a 3D footprint. Considering those un-interpreted data as starting point for further investigations, the hypothesis is to rely on a "low-level" analysis of geometric features aiming to enrich informative and scientific value of "high-level" semantic studies. This article describes an approach using discrete curvature assets to link morphological identification and semantic characterization. The mean curvature has been parametrized to highlight it use as an eloquent shape description. At this point, a comparative analysis within an architectural collection composed of similar entities would be led according to the remoteness degree compared to an average geometric reference model. The introduced principle explores the construction of curvature-based signatures so as to reassess the conceptual articulations of 31 Romanesque columns from the cloister of the abbey of Saint-Michel de Cuxa.**

***Keywords*—Architectural representation, morphological analysis, semantic characterization, discrete curvatures.**

I. Introduction

Nowadays, digital 3D scanning techniques provide great tools for conservation, documentation and promotion of cultural heritage. However, in the field of architectural surveying, these technologies enable new practices that need to contribute for cognitive and analytic plus-values all along theirs uses. Indeed, the ease of use made possible by both automated acquisition and data processing, obtaining an accurate "footprint" is no longer an end in itself [1] [2]. This gain of efficiency in terms of completeness, accuracy and quickness – now accessible and affordable to a broader audience – allows to collect an (over)load of metrical and colorimetric characteristics on an increasing numbers of object. Simultaneously, arise methodological issues for archiving, structuring and extracting from real-based model its meaningful information for analysis [3] [4].

This work focuses on surface curvature, which seems to be an appropriate descriptor to lead a morphological analysis. It continues and completes a first research which had revealed geometric discontinuities profiles within the same collection [5]. The aim of this study is to determine if and how the construction of curvature-based signatures enables and can help a shapes analysis. Thus the morphological description provided might be deepened in order to define and asset the link between geometric and semantic layout.

II. From Multiplicity Of Low-Level Data Toward Intelligibility Of High-Level Knowledgde

According to recent researches, it does'nt seems that the overgrowth of data intrinsically expands its level of intelligibility [4]. Moreover, morphological analysis of an architectural object is historically based onwards a possible interpretation of presupposed knowledges that were established and codified by the architectural treatises or dictionaries [6] [7]. This so-called "top-down" approach is no longer operating to manage large and complex dataset ones need to be manually mined. In this context, it seems more appropriate to rely on data accumulation for bringing out of itself main characteristics contained in the digital instance. This "bottom-up" approach minimizes the interpretation degree of human analysis. Thus, the latter seems like more relevant for cumulative studies, i.e. to deal with the complexity of an object's geometric properties multiplied by the amount of artifacts composing a collection.

Gauss introduced in 1928 surface curvature on non-Euclidian geometries, the principle is to define how much bends a given curve for each point of a surface. The curvature has already been implemented and used for shapes analysis of heritage artifacts [8] [9]. Such researches still request an intervention of an operator or have used the curvature map but to detect local similarities within a single object. And so, they can't be applied nor to comparison of multiple artifacts neither on analogies between several collections. For these reasons, a preliminary study was necessary in order to define an ad-hoc parameterization of the discrete curvatures for enhancing the readability of a surface [10]. It provides a framework using curvature as a suitable descriptor to link massive low-level

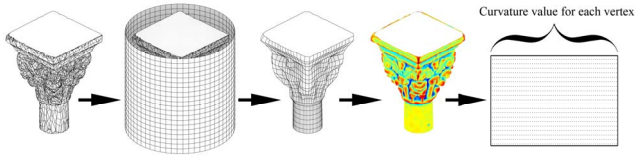

Fig. 1 Reparameterization process with regular wireframe [10]

morphological features and relevant high-level shape semantics.

III. Methodological Data Discrimination

This section describes methodological stages to construct starting from millions of three-dimensional coordinates a morphological signature that can be composed of hundreds points. All of the 31 columns of this collection have been collected during a photogrammetric survey campaign in 2010. Raw photographs and so on have been reprocessed through a common and updated protocol benefiting fully automatic image matching and advanced meshing [11] [12].

A. Pre-processing : from point set to surface reconstruction

The aim of those preliminary steps is the building of a homogeneous dataset for all artifacts. For each column, a clean and consistent (both metric and visual) point cloud is obtained including normals. A first triangular mesh is resulted from optimized parameterization of the Screened Poisson Surface Reconstruction so as to fit closest to the original point-set [12]. Then, the meshes are semi-automatically oriented in a same world space and their units fixed to their bounding-box.

B. An helpful mesh reparameterization process

A reparameterization process is aimed to turn a triangular mesh into a regular and quadrangular mesh. The principle is to project on the mesh a uniform wireframe grid. The cylinder was the geometric primitive chosen in order to fit it as close as possible at the column "Fig. 1". The batch processing has been done using MEL (Maya Embedded Language) scripting. This step is highly recommended as the goal is to compare an identical given point onto different surfaces (coming from the set of digitized columns). Indeed, thanks to it the mesh could be transcribed in tabular form and each point value (e.g. coordinates, normal, curvatures…) is comparable. As a result, the reparameterization is needed to:

- Enable extraction of point value into digital matrix.
- Guarantee the data comparison in between each model.
- Decimate the model to get faster computation but preserving a correct detail level.

C. Construction of geometrical reference model

According to an identical *M-by-N* grid parameter every mesh is composed of a same number of indexed points. Thus, it's possible to transform this reorganized point-set into an *M*N-by-X* table where *X* corresponds to a point's value (i.e. *x*, *y*, *z*, *Nx*, *Ny*, *Nz* …). Hence a 32nd geometrical average column computed from the arithmetic mean of the other 31. "Figure 2" shows, a reference model that could be calculated for each wing of the cloister:

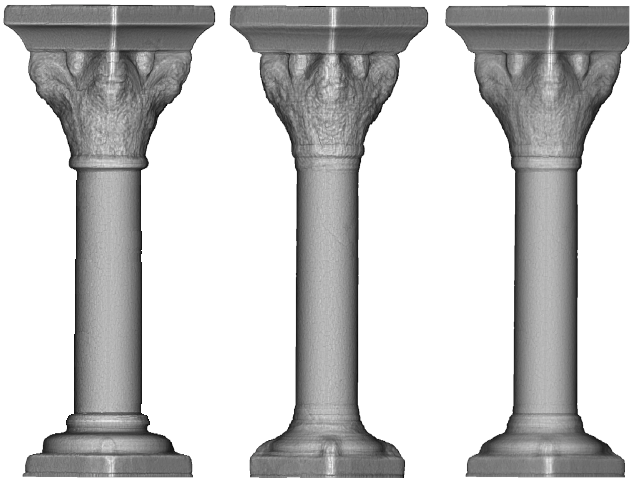

Fig. 2 Geometrical reference models (*S0*, *W0* and *C0*)

- *S0* represents average morphology of the 13 columns of the South wing.
- *W0* represents average morphology of the 12 columns of the West wing.
- *C0* represents average morphology of the 31 columns of whole cloister; including the 6 columns of the North (2) and East (4) wing.

D. Extracting curvature matrix

The discrete curvatures appear to be a key feature to describe morphological variation of an object's surface, in term of concavities and convexities. As a possible expression of the minimal surfaces, the mean curvature was chosen to fit with the discrimination aim of this study, but any other types could be applied (e.g. Gaussian, absolute, minimal or maximal) depending of observations that need to be performed. Extracted as a digital matrix, the curvature values could be manipulated and compared using shapes analysis tools, pattern recognition methods or the numerical computing. Once again, the computation of curvatures and its table is based on a "homemade" MATLAB GUI and scripts used for batching the whole collection [13].

E. Curvature-based signatures computation

A curvature matrix can be seen as a 2.5D cartographic map, i.e. a three-dimensional characteristic is stored in a bi-dimensional format. In this case the couple X and Y – respectively rows and columns of the matrix – represents a located point and Z is associated to its curvature value in a cell. One can proceed to an arithmetic mean along a pertinent dimension to obtain a signal corresponding to a real-world profile section. A so-called "signature" is defined by this one-dimensional array describing the main morphological variations related to the semantic articulations of the object. As the collection's dataset has been processing with the same reparameterization step, it allows direct comparison of shape signatures with no kind of bias (interpolation, extrapolation...).

IV. Shape Signatures And Semantics Comparison

At this point, a short review has to be done to express some asset of this approach. A template as "Figure 5" provides a first global glimpse whereof a few columns emerge

regarding their similarities and/or disparities. Therefore the following morphological analysis among statistical, geometrical and semantical point of views focuses on 4 columns from each wing (*S3*, *W24*, *N27* and *E28*). Notice that these observations were facilitated thanks to the average geometry revealed from the *C0* model; on which one can deduce some interesting findings "Fig. 2".

A. Statistic assessment

Both curvature matrix and signature as a digital signal provide capacity for quantitative approaches that can be transposed into a metric system afterwards. A reliable method has been chosen to quickly quantify variations and so to sort the four columns of this restricted case-study according to a certain degree of remoteness. First the difference to *C0* was computed to obtain a delta signal for each signature on which the standard deviation has been used to quantify with a single index their closeness to the reference model "Fig. 3". Obviously, other difference operators (e.g. cross-correlation, Dynamic Time Warping, Euclidean distance…) could be additionally used to get a finer analysis at a lower reading scale.

B. Geometric description

The sharp transition between the echinus and the historiated capital (*b*) on *C0* verifies a regular position of this upper part. Contrarily to the dimension of the abacus (*a*) on *S3*, fitting with the average, other columns present a smaller instances of this element. One can also read signature amplitude (X axis) as an indication about the state of conservation. As an example, the signal of the upper part of *W24* is smoother than the sleeked one of *C0*. But, there are no common measures with the fuzzy result of the lower part – and its un-readable signature on *W0* and so *C0* – that clearly indicates a sensitive variation of this element. One shall notice the downscaled base of the column *N27* and the difference with *S3* closest to majority proportion of these elements.

C. Semantic characterization

Semantic layer is defined as each architectural concept that could be identified according to recognizable signal, frequency or pattern on the shape signature. Moreover, most of the interesting observations enabled on the curvature matrix are still perceivable on the curvature profile; degradation on

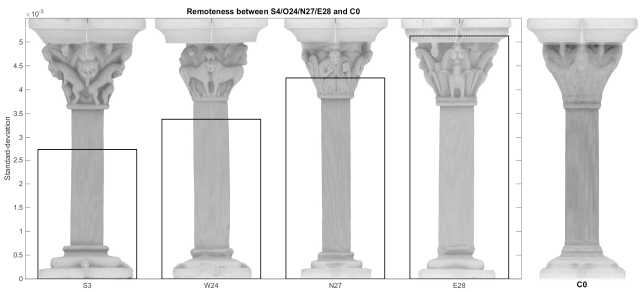

Fig. 3 Sorting the collection using the standard deviation

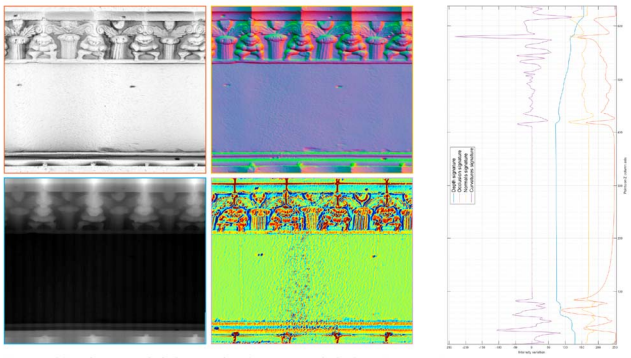

Fig. 4 Different UV maps and their respective signatures

the shaft of *W24*, such as the particular echinus (*ab*) of *E28*. The most surprising variation of the shape-semantics concerns the astragal position (*c*); lower on *S3*, upper on *W24* and *N27*, hydrid on *E28*. Despite of the lack of intelligibility of the current reference models they are complementary to previous "theoretical" models [11]. Indeed the geometric *C0* revelation is the highlighting of a doubled astragal – clearly identifiable on the signature – resulting from the different location of this entity. This revelation could have lead to recover of the original disposal of columns. Indeed, eight of the ten columns that belong to this upper position of the astragal actually correspond to the historiated capitals that were moved from the tribune to the cloister during the 1955 reconstitution.

V. Conclusions And Perspectives

The curvature-based signatures resulting from this process appeared to be a pertinent response to summarize a shape to its essential representation. Beyond a curvature signal that proves more eloquent than the original data (e.g. picture, pointcloud, mesh), this approach exposes an efficient data discrimination aiming to identify and classify both "theoritical" and "specifical" column's geometric features according to shape semantics. As a lightweight and synthetic description, it provides interesting abilities to treat and study a wide dataset. The latter needs to be extended over possibilities of cross-analysis with other artifacts or collections. For already having performed some tests, one shall notice that the current methodological process may be transposed to any other kind of UV mapping (e.g. colored texture, depth, normal, ambient-occlusion…) depending the aim of the observation "Fig. 4". This lead makes possible to enrich both description and analysis for a complementary shape reading using multiple descriptors [4]. Moreover, this extended method has already been applied on different dataset (architectural and archæological fragments) with minor adjustments and if a planar or a cylindrical projection can be used. Thus it was shown that signatures are more morphologically significative if the artifact presents symmetries.

But, to reach this goal the next step is to move forward a generic framework to get rid of the reparameterization limits. For example, one can think of an exploration of the spherical geometry and parameterization. One another may be thinking

to proceed directly on the raw data (i.e. the point cloud) to avoid bias and decimation. Even if for accurate architectural and archaeological analysis purposes, this method still remain relevant, the current geometric primitive based re-meshing and its accordance to object's shape imply few limitations:

- The inadequacy of this method to compare different morphology of large and heterogeneous collections.
- The difficulty encountered to unwrap complex geometry into table format.
- The shape approximation resulting from the wireframe projection.

The main finding of this research is the great analysis support provided and offering a valuable help for an easy and fast graphical comparison. Even though its enlightening about tendencies and remoteness of semantic variations within the collection – over and above theirs hypotheses of interpretation – we had to come back to a manual analysis. Visual analytics will have to be promoted to overpass the skill and the need of human operator to manipulate high-level knowledge. In this case, signal processing would be explored so as to reproduce the automatic detection of formal discontinuities already done before [5]. Moreover, aware of what is needed to look at, machine learning can be a way to reach the so-called "big data" processing.

In light of all of these elements, it would be interesting for a further investigation to assess and link morphological signatures compared to a shape thesaurus [7].

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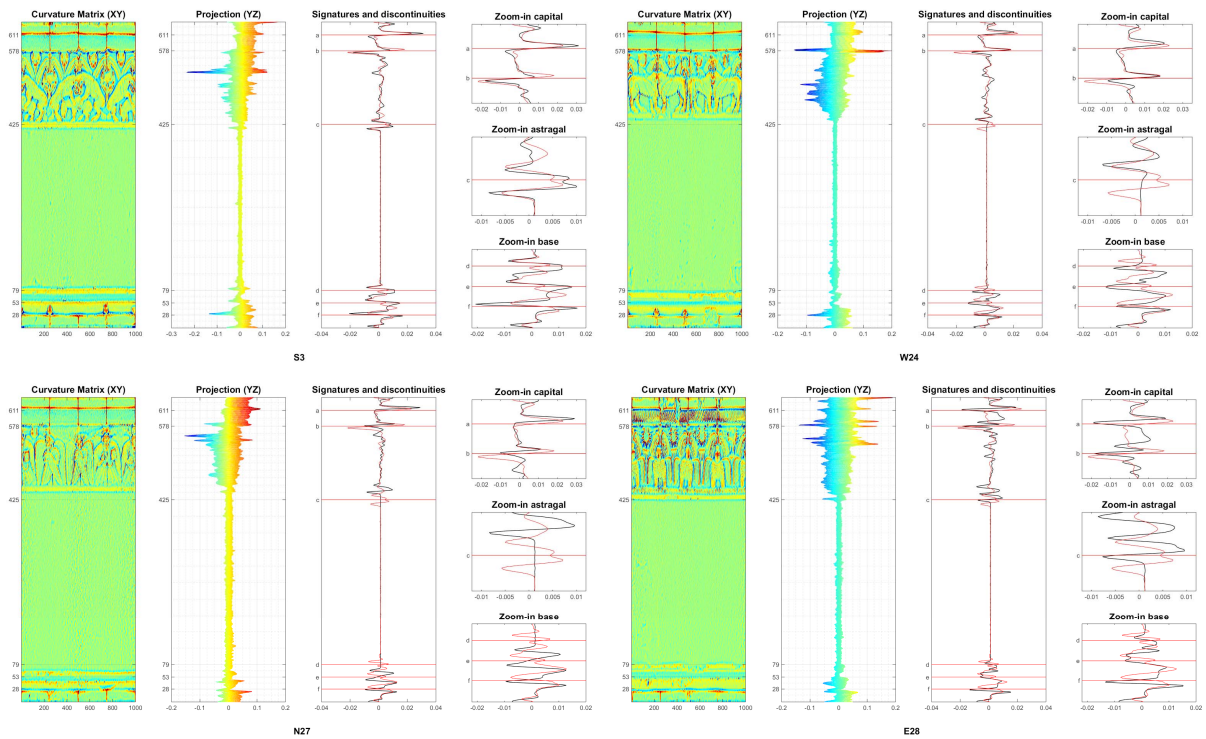

Fig. 5 Curvature graphic plots for *S3*, *W24*, *N27*, *E28* ; XY matrix, YZ projection, mean curvature signal along X and signature superimposed with *C0* profile and geometric discontinuity profiles (in red), zoom in on different parts.