Studying Shape Semantics of an Architectural Moulding Collection: Classifying Style Based on Shape Analysis Methods

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***Abstract*—As technologies for 3D acquisition become widely available, it is expected that 3D content will become increasingly popular. Nevertheless, to provide access and enable the creative use of 3D content, it is necessary to address challenges such as the availability of open repositories dedicated to 3D content and the automatic enrichment of 3D content with suitable metadata so that content does not get lost. To address these challenges, this paper presents research on developing technologies to support the organisation and discoverability of 3D content in the Cultural Heritage (CH) domain. The main contributions of the paper include an ontology for documenting 3D representations of architectural mouldings decorated with ornament. In addition, a shape analysis method to improve the information that is automatically extracted from a 3D shape is proposed. This method is tested on part of a collection of Regency ornament mouldings found in domestic interiors. This content provides a rich dataset on which to explore issues common to many CH artefacts, such as design styles, patterns and motifs.**

***Keywords*—ontologies, shape analysis, architectural mouldings**

I. Introduction

The assimilation of 3D technologies over the last few years is an undeniable fact, as demonstrated by the growing adoption of 3D entertainment, augmented reality and 3D printing. Furthermore, as technologies for 3D acquisition become widely available, it is expected that 3D content will become increasingly popular. Thus, professionals and the public alike will be able to create and contribute 3D content documenting unique as well as everyday life objects. In turn, this will unleash opportunities for creative use of these assets; underpinning the development of industries which will take advantage of the richness and tangibility of this type of content for diverse application domains, such as entertainment, conservation, design and manufacturing.

Nevertheless, to achieve this vision it is necessary to address some challenges. Currently, one major problem is the lack of underpinning technologies which can ensure the automatic enrichment of 3D content with suitable metadata so that content does not get easily lost. To address this challenge, this paper presents research on developing technologies to support the organisation and discoverability of 3D content. Hence, the research contributes to address one of the major barriers for the ubiquitous use of 3D content, which is the access to 3D content at the right place and time. This barrier is mainly caused by a lack of open repositories dedicated to 3D content. Most importantly, however, it is caused by shortcomings in existing technologies needed for the automatic analysis and enrichment of 3D content with its high level semantic meaning.

The research focuses on 3D content from the Cultural Heritage (CH) domain. Specifically, we use Regency ornament mouldings found in domestic interiors. This content provides a rich dataset on which to explore issues such as design styles, patterns and motifs. It also provides a suitable contribution to the Cultural Heritage domain, where many artefacts and architectural elements are decorated using patterns and motifs relevant to a time period and place.

The main contributions of the paper include part of an ontology for documenting 3D representations of architectural mouldings decorated with ornament. This ontology is developed alongside a shape analysis method to improve the information that is automatically extracted from a 3D shape. This will allow a variety of users to interrogate a repository using the underlying semantic connections within the content, rather than its low level geometric information (e.g. name or size of a 3D mesh).

The paper is organised as follows. Section II presents an overview of related work in the area of semantic analysis of 3D content. Section III provides background information in the use of ornament to decorate architectural elements, in particular during the Regency period in Great Britain. Moreover, section IV describes the main elements of an ontology to document an architectural moulding collection. Section V presents the saliency based shape retrieval method which is proposed to study the shape semantics of the collection, while section VI shows the results of the current implementation. Finally, section VII presents conclusions and further work.

II. Related work

Once artefacts are digitised using 3D acquisition technologies, the resulting 3D content is usually kept stored in a computer, hard drive or uploaded into an online repository. The latter option is usually the less popular option as 3D repositories are still in its infancy and existing repositories have mainly resulted from research projects, including the Digital Shape Workbench [1], the Princeton University repository [2] and the 3D-COFORM repository [3].

Whatever the mechanism for storage, 3D content is at risk of being lost if there is no meaningful information associated

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with it. Although this problem is common to other content, such as text documents or images; 3D content has inherently richer semantic information associated with its shape than other content types. By semantic information we mean the collection of facts about an object within a given domain.

Artefacts from the cultural heritage domain are described in a way that depends on the professional (e.g. curator, art historian) providing that description. As with other fields, different views on the object might be of particular interest in order to convey its most important characteristics. According to Hudson [4], artworks are typically described in terms of their basic components (e.g. colour, shape, value, texture, space, time and motion, sound and smell), principles of design (e.g. balance, unity and variety, proportion and scale, and rhythm), medium (e.g. physical material used in the work), and style (e.g. a particular period style). It is important to note that only a few of these elements can be automatically extracted from a digitised 3D shape; although it is possible that others can be inferred.

Hence, semantic information related to a cultural heritage artefact might be intrinsic or extrinsic to the shape itself. For instance, style is used as a descriptor to classify an artefact within a specific time period, place, art movement or school. As such, style is related to the visual appearance of the artefact and can relate an artefact to others in the same style. However, the required knowledge to determine the style of an artefact is usually stored in the head of experts who are trained to observe the shape of artefacts as well as ornament patterns and motifs used across history to decorate artefacts.

Solutions for understanding and interacting with the semantic-less 3D content rely on shape analysis methods, including segmentation ([5], [6]), labelling, classification, matching, recognition and retrieval methods. Existing solutions for semantic enrichment provide manual or semi-automatic mechanisms for understanding the semantic meaning of shapes ([7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]). These solutions rely on different shape segmentation approaches as well as labelling or manually connecting the shape (or part of it) to a semantic network with relevant information on the knowledge domain. Most solutions attempt to understand what a shape represents, rather than study the shape to extract other relevant information which might help for its classification.

Of relevance to this work is the research of Buglio et al. [17] who propose a bottom up approach to characterise the features of architectural columns. Their approach is based on the analysis of the low level geometric properties of a collection of columns. Our approach also looks at architectural elements of historic domestic interiors. However, our approach focuses on studying their decoration to extract semantic meaning of the 3D shape. Hence, the proposed automatic method classifies the 3D content according to artistic style and likely production methods.

The following section will describe essential background on the use of ornament to decorate domestic interior, in particular focusing on the Regency period in the United Kingdom.

III. Architectural ornament for the decoration of historic domestic interiors

Meyer [18] defines the term decoration as the art of applying ornament to beautify objects. The style of decoration is usually determined by the aim and material of the object to be decorated and, secondly, by the ideas ruling at different periods and among different nations. Phillips and Bunce [19] trace patterns used in ornament from ancient and classical times through to the Gothic and Victorian periods, and culminating in the high-tech computer-aided designs we use today. Jones [20] presents a comprehensive history of ornament along different periods and nations from antiquity to the medieval and the Renaissance in Europe, India, China, Pacific islands and the Islamic world. In this work, Jones defines style in architecture as the peculiar form that expression takes under the influence of climate and materials at command.

Furthermore, *pattern* used in ornament is defined as a design composed of one or more motifs, multiplied and arranged in an orderly sequence [19]. *Motif* is defined as a unit with which the designer composes a pattern by repeating it at regular intervals over a surface [19]. Meyer [18] makes a further distinction between organic (e.g. natural foliage, animals, human figures) and inorganic (e.g. geometrical elements) motifs. According to these definitions, artefacts decorated with ornament can be classified as follows:

- By their historical and cultural origin,
- By the type of imagery used for the elements of the motifs, and
- By the organisation of the motifs that forms the structure of the patterns

This research focuses in particular on ornament used to decorate interior of buildings during the Regency period and others trying to emulate this style. Regency Britain was a marvellous period for the visual arts. This period is known as the time in which George IV acted as Regent (starting in 1811), in place of George III who was seriously ill. In 1820, George IV was proclaimed king of Great Britain. However, the Regency period is not constrained by these political events. Experts can trace Regency style expressions from as early as 1780 until 1840, when the Victorian style starts to be identified. Regency is also a unique style which was exported to the United States having a substantial influence on American design at the time of the Federal and Empire eras of architecture and decoration [21].

According to Parissen [21] the historical events of this era reflected on the choice of materials and processes used for the architectural detailing of the Regency home. During this period, plaster and composition plaster became a popular choice for decorating the interior of buildings and households. Figure 1 shows examples of plaster ceiling roses with a Regency style. The city of Brighton and Hove, in the South East of the England, has many areas with a distinctive Regency style of buildings. As such, the interest in the use of plaster mouldings to decorate architectural elements both in interior and exterior of buildings remains high amongst heritage professionals and the public in general.

Historically, mouldings have been produced by either running or casting the material using a mould. Running requires

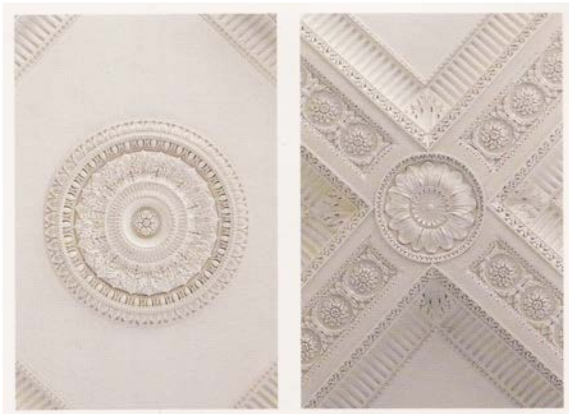

Fig. 1. Regency style plaster decoration for buildings interiors [21]

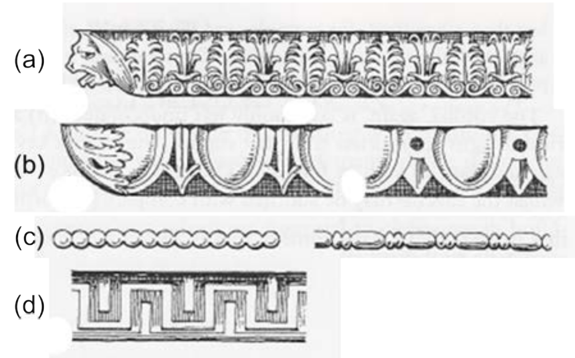

Fig. 2. Patterns commonly used in Regency style mouldings in household interiors. a) pattern with anthemion and palmette motif; b) egg and dart; c) bead and reel; and d) fret pattern [23]

of a wooden running mould with a sharp zinc profile defining a cross section. This mould is then run through the plaster along its length to produce the moulding. Casting is a more complex process, as it requires of a mould in which plaster can be poured and retrieved when this has solidified. When using plaster material, the moulding's master or *buck* was traditionally carved in wood. Moulds were then produced using resin or rubber which was poured over the *buck* to create an exact impression. Many plaster mouldings could then be produced using this mould until it wore out and another mould was produced.

Composition plaster was another commonly used material, and it differs from traditional plaster as it is produced by a mixture of ingredients, such as chalk, glue, linseed oil and resin [22]. The composition mouldings did not require a *buck* as the ornament was carved directly into wooden moulds with extraordinary delicacy and precision. Hence, composition plaster was poured directly into the wooden moulds to produce the mouldings.

The vocabulary of motifs and patterns of Regency plasterers was influenced by Neo-Classical motifs. The more important the room, the heavier and more profuse the moulded ornamentation was. Figure 2 illustrates some commonly used patterns, including:

- Anthemion and palmette moulding: pattern comprising alternating palmette and anthemion motifs. The term anthemion comes from the Greek term for *flower*. The palmette is a motif resembling a stylized erect leaf divided into lobes, in the form of a fan or palm leaf, often supported by spirals.
- Egg and dart moulding: pattern of egg-shaped motif alternating with dart like motif.
- Bead and reel moulding: pattern with disks alternating singly or in pairs with oblong beads.
- Fret moulding: Patterns consisting of repeated, linear, geometrical shapes, usually angular, in a continuous band.

For this research we had access to the prestigious Jackson ornament collection provided by r the Regency Town House [24]. This collection comprises of mouldings (plaster or composite plaster), reverse cut moulds and *bucks* (in hardwood and soft wood) used for decorating wall and ceiling spaces. It was assembled by the ornamental firm George Jackson and Sons through the 19th and 20th centuries.

We have initially scanned 20 objects from the Jackson collection using the Breuckmann smartscan device [25]. This selection included a mixture of mouldings as well as wood moulds.

IV. Semantic ontology to describe the architectural moulding collection

The Jackson collection is complemented by an existent database with information such as a unique identifier, any historical marks, location, and a free text description. Also, the database contains information on the locations, when known, where copies of the mouldings are being used and the artist who designed the master or mould.

This conceptual organisation of the current data on the collection was mapped and enriched with additional information using the CIDOC Conceptual Reference Model (CRM). CIDOC-CRM [26] provides a formal structure for describing the implicit and explicit concepts and relationships used in CH documentation. As such, the main objectives of this process was twofold: 1) to capture the information related to the processes, materials and visual elements used for this particular domain; and 2) to link to the digital files produced during the scanning process or other information related to the collection (including that existing in other databases).

Luca [27] introduces the principle of points of view in order to structure semantically enriched 3D models representing architectural elements. The proposed ontology focuses mainly on the mouldings point of view of architectural elements. Hence, it does not attempt to describe the individual elements of a building but instead focuses on mouldings, wherever these happen to be located, and their production method.

We present part of the resulting CIDOC-CRM model which describes the information related to the decoration style. Other parts of the ontology refer to the who, where and when the elements of the collection were produced. Figure 3 shows a section of the ontology which captures the knowledge of the production of mouldings, particularly but not restricted, for the

Regency period. Therefore, we model an "E12 Production" event linked to the "E84 Information Carrier" concept, which describes the resulting moulding. In order to model how the moulding was produced, we use another "E84 Information Carrier" concept to describe the mould, which in turn is linked to its own production event ("E12 Production"). Moreover, the production of the mould (when required) is modelled through another "E12 Production" concept which is further linked to an "E84 Information Carrier" concept describing the *buck*.

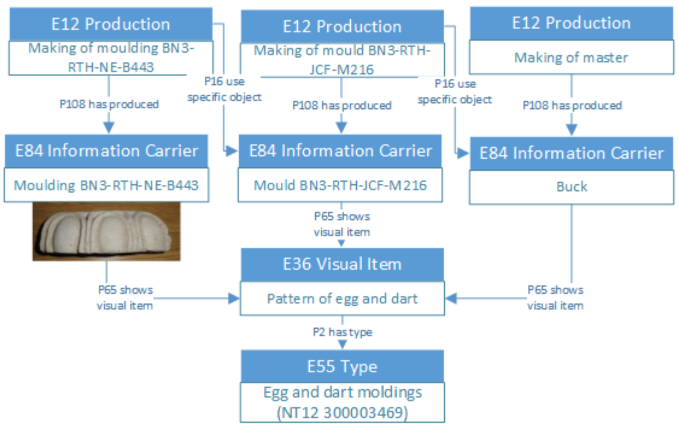

Fig. 3. Part of the ontology describing the plaster moulding production and the artistic style of the mouldings

In addition, all of the "E84 Information Carrier" concepts are linked to the "E36 Visual Item" concept. This concept is used to describe cross sections, ornament patterns and/or motifs shown in any of the mouldings, moulds or *bucks*. The "E36 Visual Item" concept is also linked to a particular style using the "E55 Type" concept. As such, we conceptualise artistic style by characterising similar physical features which are shared by all objects from the same style despite of when these objects were produced. As such, Regency style objects could have been produced in 1810 or today.

In order to have a vocabulary to describe the different types of cross sections, patterns and motifs, we use the Getty Art & Architecture Thesaurus (ATT) [28]. This thesaurus includes elements commonly used in Regency mouldings, such as egg and dart, bead and reel as well as fret mouldings.

In addition, CRMdig [29] is used to link the "E84 Information Carrier" to its corresponding scanned mesh ("D9 Data Object"). This link enables the shape analysis method to query those 3D meshes with known styles in order to enrich those shapes with unknown styles. As such, we can automatically enrich shapes with concepts such as pattern/motif and style. The shape retrieval method is described in the following section followed by initial results.

V. Saliency-guided shape retrieval

A. Shape saliency

In this paper, we present a novel shape retrieval method based on shape saliency. 3D shape saliency, first proposed in [30], is a measure of regional importance based on human perception. On one hand, the saliency map of a 3D shape highlights the most important geometric features on the surface. On the other hand, it is not just about shape geometry. Some experiments have been conducted to demonstrate that the computational model of shape saliency has better correlation with human eye fixations than a random model and a curvature-based model [31]. Thus in computer graphics, it is very promising for solving problems related to semantic analysis of 3D shapes. This has recently motivated many researchers [32], [33], [34], [35], [36], [37], [38] to investigate various computational saliency models.

We propose a novel algorithm for computing shape saliency based on *stochastic Laplacian*. Given a shape as a triangulated mesh M, we first calculate its Laplacian matrix. Typically, the Laplacian matrix of a mesh is based on the discretisation of a continuous Laplacian (e.g., the Laplace-Beltrami operator) defined (mathematically) for a smooth manifold using some weighted sum of adjacent vertices [39]. If a mesh M contains m vertices $p_1, \ldots, p_m$, in its simplest form, the Laplacian matrix can be computed as:

$$L = D - A \tag{1}$$

where A is the adjacency matrix, given by

$$A(i,j) = \begin{cases} 1 & \text{if } p_i \text{ and } p_j \text{ are neighbours} \\ 0 & \text{otherwise} \end{cases}, \tag{2}$$

and D is a diagonal matrix in which D_{ii} is the degree of vertex p_i. This simplest computational model merely takes into account the combinatorics (connectivity). Ideally, a multi-scale representation should not only describe the combinatory structure of the mesh, but also encode its local geometric details. To incorporate local small-scale geometric information, the adjacency matrix is weighted by the distances between neighbouring vertices:

$$W(i,j) = \frac{1}{\|p_i - p_j\|^2} A(i,j); \tag{3}$$

This leads to the mesh Laplacian

$$L = D - W \tag{4}$$

We employ Eq. (3) other than the widely used cotangent because we find that it benefits the detection of salient features. The largest angle in an ill-shaped triangle has a negative cotangent but with a large absolute value. Since we need to compute the absolute values of the elements of the Laplacian to transfer it to a stochastic matrix, in the experiments we found that the cotangent Laplacian leads to high saliency values on ill-shaped triangles. The proposed mesh Laplacian is more meaningful in terms of salient features since usually most meshes retain more vertices around features (e.g., shape extremities). And we also observed that the cotangent Laplacian is not so efficient as the mesh Laplacian.

In this work, Eq. (4) is followed by two steps. First, we compute $\widehat{L}$ composed of the absolute values of the elements of the mesh Laplacian: $\widehat{L}_{ij} = |L_{ij}|$. Second, we normalise $\widehat{L}$ subsequently so that the sum of each row is 1

$$\mathcal{L} = \left[\widehat{L}\right]_r \tag{5}$$

where $[\cdot]_r$ denotes the row-based normalisation.

These two steps are very important since it actually turns the mesh Laplacian to the so-called *stochastic Laplacian*.

Algorithm 1: Saliency detection

Data: A mesh M represented by a vertex matrix P and a face matrix T
Result: A saliency map I
begin
  Compute $\widehat{L}$ and then the stochastic Laplacian $\mathcal{L}$, input the number of scales as K and input a precision value λ;
  $F^{(1)} = \mathcal{L}$;
  for $k \leftarrow 2$ ***to*** K **do**
    $F^{(k)} = F^{(k-1)}\widehat{L}$;
    $\mathcal{F} = \left[F^{(k)}\right]_r$;
    for $i \leftarrow 1$ ***to*** m **do**
      for $j \leftarrow 1$ ***to*** m **do**
        if $\mathcal{F}(i,j) < \lambda$ **then**
          $\mathcal{F}(i,j) = 0$
    $F^{(k)} = \mathcal{F}$;
    $\mathcal{D}^{(k)} = \left|F^{(k)} - F^{(k-1)}\right|$;
    Calculate the difference map as $D^{(k)} = \sum_r \mathcal{D}^{(k)}$ where $\sum_r$ denotes the row-based summation;
  $\mathcal{I} = \sum_{k=2}^{K} D^{(k)}$;
  $I = \log(\mathcal{I})$
end

We first explicitly give our algorithm for computing shape saliency in Algorithm 1. It is based on the iterative updates of the stochastic Laplacian through matrix multiplication, and can be implemented much more easily and efficiently than previous methods which require eigendecomposition of the Laplacian or the design and dilation of wavelets. In the following, we analyse the algorithm and explain why it works.

The row based normalisation $\mathcal{F} = \left[F^{(k)}\right]_r$ in Algorithm 1 guarantees that the vertex matrix is updated by a stochastic matrix in each iteration, which in fact describes the transitions of a Markov chain. It is known that for a stochastic matrix $\mathcal{F}$, $\mathcal{F}_{ij}$ denotes the probability of the one-step transition. Therefore, the k-th stochastic Laplacian produced through a series of $k-1$ matrix multiplications gives the k-step transition probability. Since the matrix of stochastic Laplacian is sparse and here we also set a precision value λ to rule out small entries, most transitions are prohibitive (transition probability equals zero). And, only the transitions within a neighbourhood is available because it is constructed based on the adjacency matrix. Hence, the k-step transition actually defines a connected k-ring neighbourhood while all other connectivities/paths are prohibited. And when we perform the multiplication $P^{(k)} = FP$ in Algorithm 1, we essentially perform a displacement in a k-ring neighbourhood for each vertex. Such a vertex displacement leads to the loss of local surface details and a hierarchy of meshes with multiple scales of details is formed. The more salient the vertices, the more the loss of corresponding local details. Therefore, we calculate the shape saliency as the aggregation of the difference maps at all scales excluding the first one in order to avoid being affected by noise perturbation. We finally output the saliency map I by computing the logarithm of $\mathcal{I}$ merely for a better visualisation effect. Some results using shapes from the Jackson collection are shown in Fig. 4.

In Fig. 4, it can be seen that the detected salient regions are typically the most representative and informative features of the shape in a semantic sense. And more importantly, it shows some correspondence. For instance, the egg and dart pattern is always detected as a salient region in different shapes. In general, shapes which can be categorised into the same semantic group could have highly correspondent salient features. This finding inspired us to develop an automatic shape retrieval system.

B. Shape retrieval method

After detecting the saliency of a shape, we extract the salient vertices corresponding to the representative and informative features of the shape. We first extract the vertices with a saliency value larger than a predefined threshold. Then we further refine the set of salient vertices by removing the ones located on boundaries which are less reliable since most of the boundaries are caused by holes, missing data or poor sensing and alignment of 3D scans. We also remove the isolated vertices including the 'semi-isolated' ones which are vertices with less than 4 neighbouring vertices. The outcome of such a saliency-guided feature extraction and refinement is a group of salient vertices which reliably describe the most important semantics of the shape.

Next, we normalise all of the saliency values and calculate the histogram where we use 32 bins. Each histogram is then normalised by its mean value for the following retrieval purpose. In this way, we generate the so-called shape descriptor for each shape. Figure 5 shows the shape descriptors of some shapes using the proposed method. It can be seen that similar shapes have similar shape descriptors. To retrieve a query shape means to find its best matches from a collection of shapes via some dissimilarity measure. As suggested in [40], the L_1 norm outperforms some other dissimilarity measures including the L_2 norm, χ^2 statistic and Bhattacharyya distance, etc. Thus in this work, we measure the dissimilarity of two shapes as the L_1 norm of the difference between their corresponding shape descriptors.

VI. Retrieval results

We have tested the shape retrieval method described on the previous section on the scanned meshes of the Jackson collection. On average, each shape is composed of 1.1 million vertices. It is very inefficient to analyse so many large shapes. Figure 6 demonstrates that the proposed saliency method is insensitive to simplification. In practice, we always employ QSlim [41] to simplify the input shapes.

Figure 7 shows the results of the proposed saliency-guided shape retrieval. We assume that at least some shapes in the database contain some semantic information regarding their patterns/motif and style (as described in section IV). These shapes will enable the classification of those 3D shapes that do not have semantic information linked to them. For the first four queries in the first column in Fig. 7, the method successfully retrieves other shapes which are linked to an entry of "Pattern of egg and dart" (E36 Visual Item) in their semantic network (see Fig. 3). A voting system using all

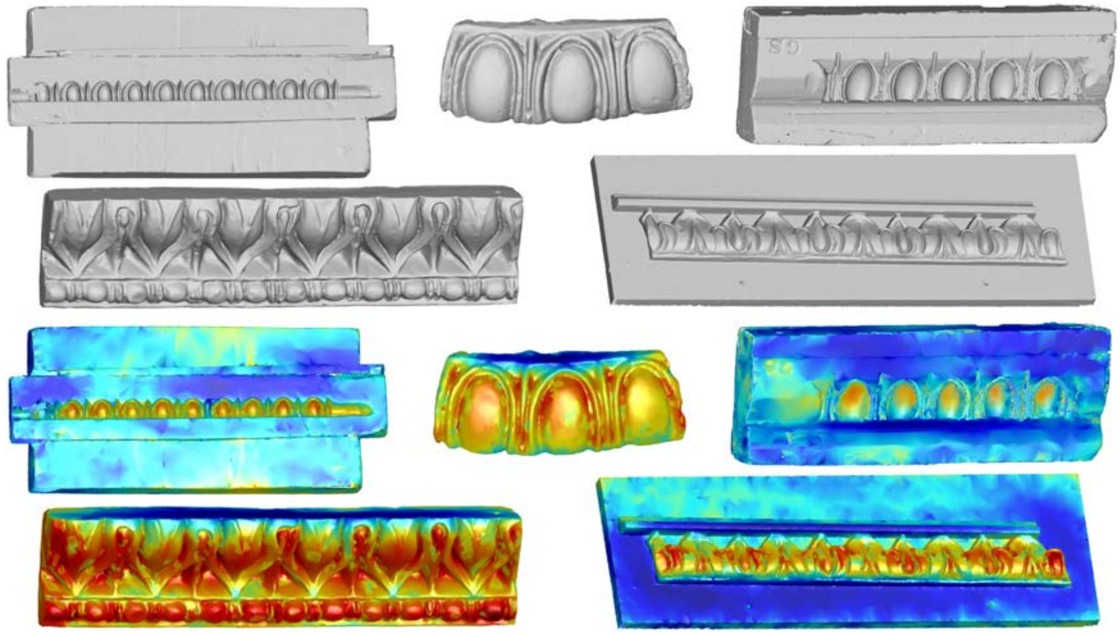

Fig. 4. Saliency detection on meshes. Top half: Original shapes; Bottom half: Saliency maps where warmer colour denotes salient regions.

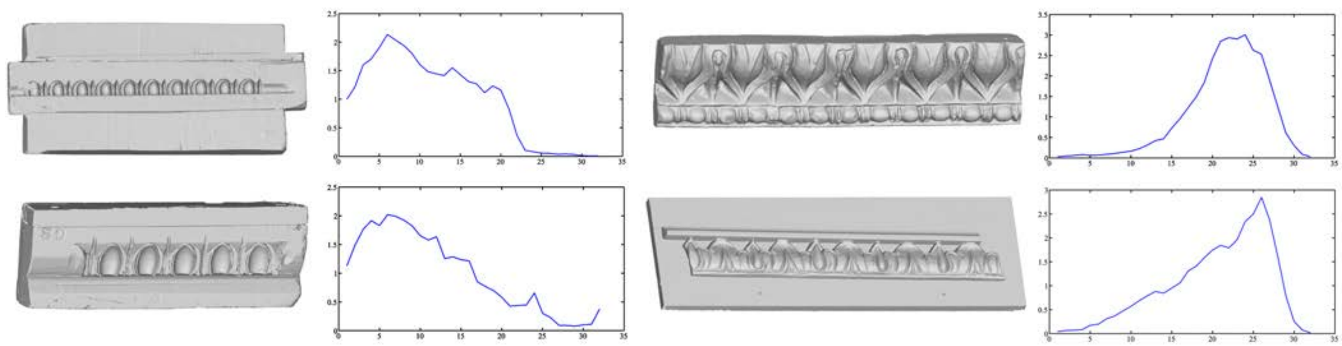

Fig. 5. Four shapes and their corresponding shape descriptors

results might easily eliminate the odd shape which is also retrieve as part of the results. The fifth query is a more complex shape, as it comprises of more than one pattern. This shape is a combination of the pattern of egg and dart and the pattern of bead and reel. The retrieved shapes show that the method can still retrieve shapes which show both types of patterns. Although, the method is currently not robust enough to understand how many patterns or motifs are present in the shape. Hence, a voting system might restrict the number of semantic links that might be made for a given shape.

We also note that the shapes which result from the shape retrieval method include mouldings, moulds and *bucks*. Shape wise, there is no distinction between a moulding and a *buck*. This distinction is usually made by the material of the object rather than by its shape. In addition, moulds contain a large amount of flat surface. Hence, the large amount of flat surfaces in some shapes in Fig. 7 is not relevant when determining the saliency of the shape. Nevertheless, these flat regions can potentially reveal some information regarding the type of object this shape represents (e.g. mould or moulding). This could be useful when there is limited information on the shape and it needs to be determined whether this is a moulding or a mould.

Computationally, we have compared our method to the state-of-the-art D2 shape descriptor [40]. The results of this comparison, shown in Fig. 8, demonstrate that the retrieval results are more semantically meaningful using our method. The results also demonstrate that saliency information can deliver an effective retrieval of 3D shapes which partially contain similar patterns and motifs. We believe this method has potential for heritage applications where most of the shapes contain informative features to understand what an object is but also when it could have been made or its artistic style.

VII. Conclusion

This paper presented research contributing towards the semantic enrichment of 3D repositories, in particular focusing on 3D representations of plaster mouldings. An ontology is used to describe architectural mouldings decorated with ornament and is complemented by a saliency-guided shape retrieval method which identifies similar mouldings. This mechanism allows the enrichment of the 3D models with information regarding their artistic style and production mechanism.

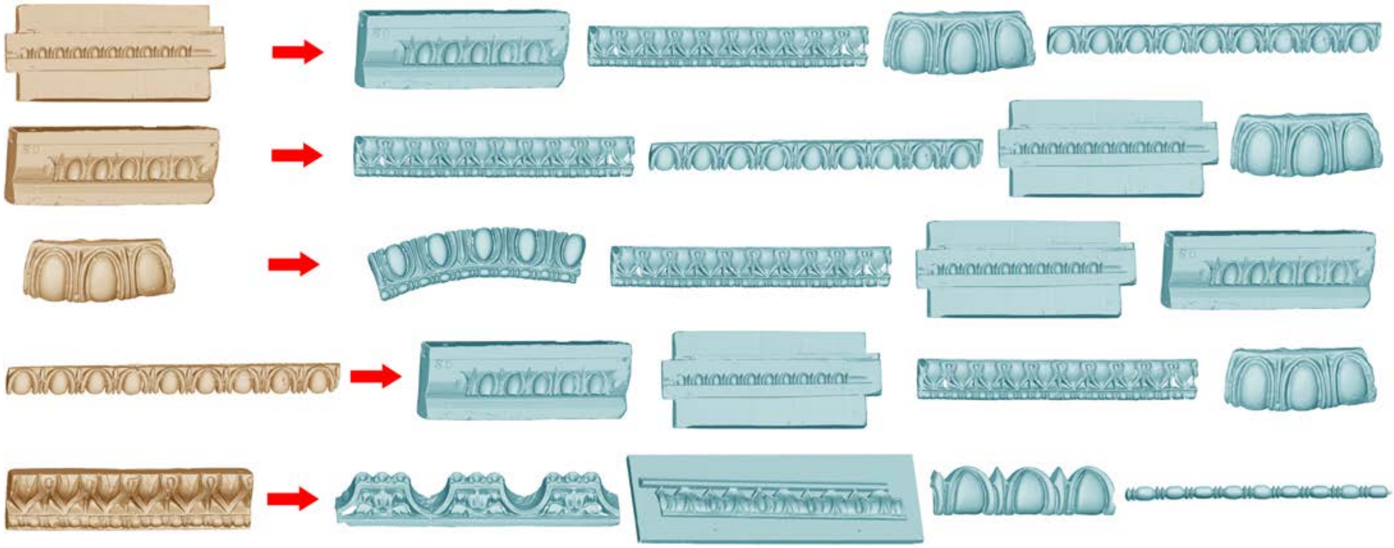

Fig. 7. Examples of query shapes (first column) selected from the Jackson collection shape database and their corresponding top four retrieved shapes using the proposed saliency-guided method

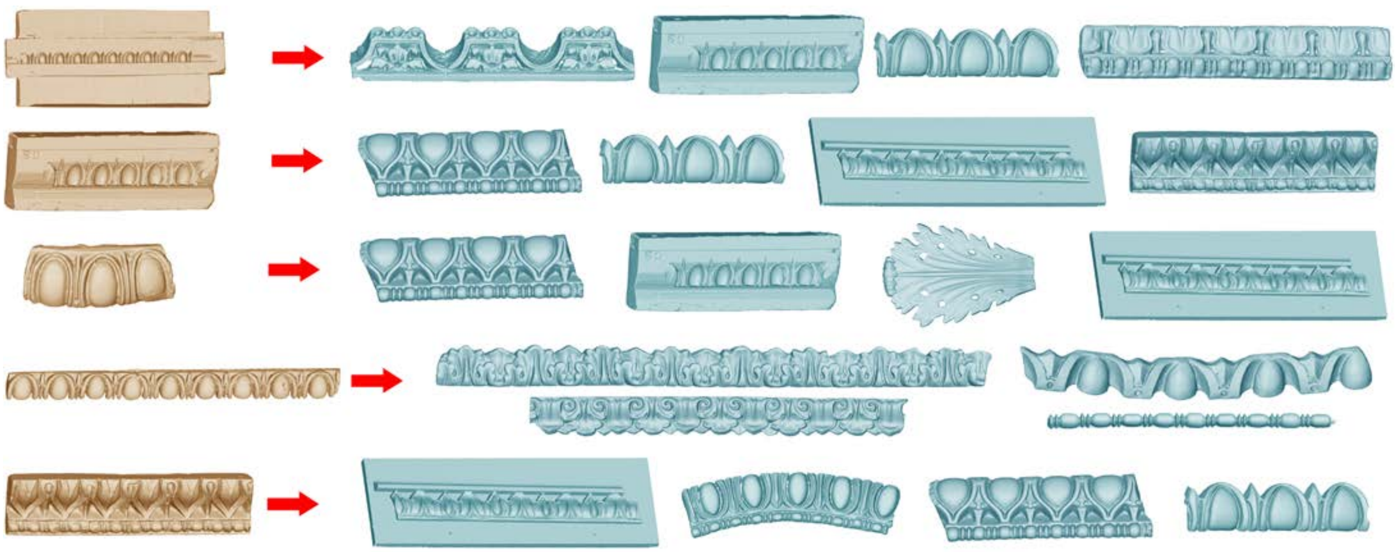

Fig. 8. Examples of query shapes (first column) selected from the Jackson collection database and their corresponding top four retrieved shapes using the D2 method

One of the advantages of our approach is that it can be applied to other heritage artefacts. In particular, it can be applied to those artefacts with some type of decorative ornament. The shape analysis algorithm could also be applied to a variety of heritage shapes to learn more about their semantic meaning. However, the main disadvantage of the current implementation is that it is unable to segment each individual pattern when more than one is used. This will require further work on segmentation of each pattern on a shape. Additionally, further works also involves including further shapes typologies, design styles as well as a greater variety of patterns and motifs.

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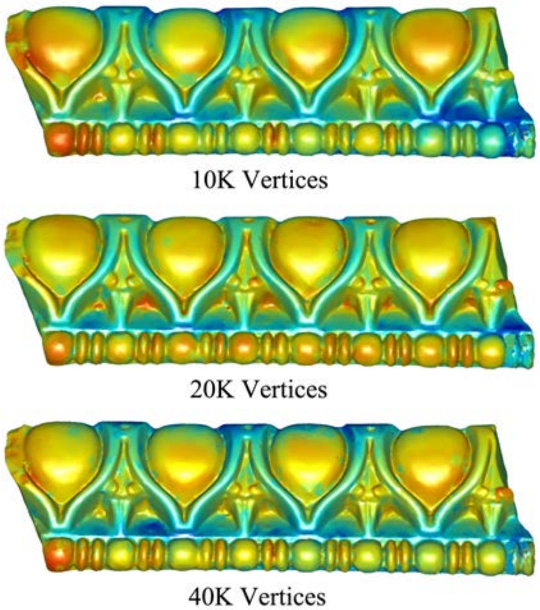

Fig. 6. Saliency of shapes containing different numbers of vertices

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