RETRIEVAL OF 3D OBJECTS USING CURVATURE CORRELOGRAMS

G. Antini, S. Berretti, A. Del Bimbo, P. Pala

Dipartimento Sistemi e Informatica
University of Firenze
Firenze, Italy
{antini,berretti,delbimbo,pala}@dsi.unifi.it

ABSTRACT

Along with images and videos, 3D models have raised a certain interest for a number of reasons, including advancements in 3D hardware and software technologies, their ever decreasing prices and increasing availability, affordable 3D authoring tools, and the establishment of open standards for 3D data interchange. The resulting proliferation of 3D models demands for tools supporting their effective and efficient management, including archival and retrieval.

In order to support effective retrieval by content of 3D objects and enable retrieval by object parts, information about local object structure should be combined with spatial information on object surface. In this paper, as a solution to this requirement, we present a method relying on curvature correlograms to perform description and retrieval by content of 3D objects.

Experimental results are presented both to show results of sample queries by content and to compare—in terms of precision/recall figures—the proposed solution to alternative techniques.

1. INTRODUCTION

Beside image and video databases, archives of 3D models have recently gained increasing attention for a number of reasons: advancements in 3D hardware and software technologies, their ever increasing availability at affordable costs, and the establishment of open standards for 3D data interchange (e.g. VRML, X3D).

Three-dimensional acquisition of a real-world object, capturing both object geometry and its visual features (surface color and texture), can be achieved through many different techniques, including CAD, 3D laser scanners, structured light systems and photogrammetry. Thanks to the availability of these technologies, 3D models are being created and employed in a wide range of application domains, including medicine, computer aided design and engineering, and cultural heritage.

In this framework the development of techniques to enable retrieval by content of 3D models assumes an ever increasing relevance. This is particularly the case in the fields of cultural heritage and historical relics, where there is a growing interest in solutions enabling preservation of relevant artworks (e.g. vases, sculptures, and handicrafts) as well as cataloguing and retrieval by content. In these fields, retrieval by content can be employed to detect commonalities between 3D objects (e.g. the "signature" of the artist) or to monitor the temporal evolution of a defect (e.g. the amount of bending for wooden tables).

1.1. Retrieval of 3D models

Methods addressing retrieval of 3D models can be distinguished based on different aspects, such as the type of representation used for geometry, the use of information about models' appearance (i.e. colour and/or texture), the need for manual annotation.

Generally, two broad classes of approaches can be distinguished: *view-based* and *structure-based*. In the former, salient features of an object are extracted from a set of 2D views of the object itself. In the latter, object features are computed directly in the three-dimensional space in order to capture prominent characteristics of the object structure.

Description and retrieval of 3D objects based on description and retrieval of 2D views has been addressed in [1] and [2]. However, the effectiveness of these solutions is limited to description and retrieval of simple objects. In fact, as complex objects are considered, occlusions prevent to capture distinguishing 3D features using 2D views.

Recently, a hybrid approach—that is not entirely view-based or structure-based—has been proposed in [9] relying on the use of spin images for content description and matching. Description of 3D structure for the purpose of recognition or retrieval has been addressed for some time. A few authors have investigated analytical 3D models, but this is not always a viable solution, as there are many lim-

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itations in providing parameterizations of arbitrary models. In [3] retrieval of 3D objects based on similarity of surface segments is addressed. Surface segments model potential docking sites of molecular structures.

Much attention has been recently devoted to free-form (i.e. polygonal) meshes. The system developed within the Nefertiti project supports retrieval of 3D models based on both geometry and appearance (i.e. colour and texture) [4]. Also Kolonias et al. have used dimensions of the bounding box (i.e. its aspect ratios) and a binary voxel-based representation of geometry [5]. They further relied on a third feature, namely a set of paths, outlining the shape (*model routes*). In [6] a method is proposed to select feature points which relies on the evaluation of Gaussian and median curvature maxima, as well as of torsion maxima on the surface. In [7], Elad et al. use moments (up to the 4-7th order) of surface points as basic features to support retrieval of 3D models. Differently from the case of 2D images, evaluation of moments is not affected by (self-)occlusions.

In order to capture geometric features as well as their arrangement on the object surface, in [8] description and retrieval of 3D objects is accomplished through a combination of warping and projection. However, this method can be applied only to objects whose surface defines the boundary of a simply connected 3D region. Moreover, warping may introduce irregular deformation of the object surface before its projection on a 2D map.

Correlograms have been previously used with success for retrieval of images based on color content[14]. In particular, with respect to description based on histograms of local features, correlograms enable also encoding of information about the relative localization of local features. In [15], histograms of surface curvature have been used to support description and retrieval of 3D objects. However, since histograms do not include any spatial information, the system is liable to false positives.

In this paper, we present a model for representation and retrieval of 3D objects based on curvature correlograms. Correlograms are used to encode information about curvature values and their localization on the object surface. For this peculiarity, description of 3D objects based on correlograms of curvature proves to be very effective for the purpose of content based retrieval of 3D objects.

This paper is organized as follows: in Sect.2 representation of object structure through curvature correlograms is presented; in Sect.3 some distance measures are defined to be used for computing the similairty between two curvature correlograms; finally, in Sect.4 experimental results and performance comparison with alternative approaches are presented.

2. COMPUTATION OF CURVATURE CORRELOGRAMS

High resolution 3D models obtained through scanning of real world objects are often affected by high frequency noise, due to either the scanning device or the subsequent registration process. Hence, smoothing is required to cope with such models for the purpose of extracting their salient features. This is especially true if salient features are related to differential properties of mesh surface (e.g. surface curvature).

Selection of a smoothing filter is a critical step, as application of some filters entails changes in the shape of the models. In the proposed solution, we adopted the filter first proposed by Taubin [10]. This filter, also known as $\lambda|\mu$ filter, operates iteratively, and interleaves a Laplacian smoothing weighed by λ with a second smoothing weighed with a negative factor μ ($\lambda > 0$, $\mu < -\lambda < 0$). This second step is introduced to preserve the model's original shape.

Let $\mathcal{M}$ be a mesh. We denote with E, V e F, the sets of all *edges*, *vertices* and *faces* of the mesh. With N_V, N_E and N_F, we denote the cardinality of sets V, E and F.

Given a vertex $v \in \mathcal{M}$, the principal curvature of $\mathcal{M}$ at vertex v is indicated as $k_1(v)$ and $k_2(v)$. The mean curvature $\bar{k}_v$ is related to the principal curvature $k_1(v)$ and $k_2(v)$ by the equation:

$$\bar{k}_v = \frac{k_1(v) + k_2(v)}{2}$$

Details about computation of the principal and mean curvature for a mesh can be found in [11].

Values of the mean curvature are quantized into $2N+1$ classes of discrete values. For this purpose, a quantization module processes the mean curvature value through a stair-step function so that many neighboring values are mapped to one output value:

$$\mathcal{Q}(\bar{k}) \quad = \quad \begin{cases} N\Delta & \text{if} \quad \bar{k} > N\Delta \\ i\Delta & \text{if} \quad \bar{k} \in [i\Delta, (i+1)\Delta) \\ -i\Delta & \text{if} \quad \bar{k} \in [-i\Delta, -(i+1)\Delta) \\ -N\Delta & \text{if} \quad \bar{k} < -N\Delta \end{cases} \qquad (1)$$

with $i \in \{0, \ldots, N-1\}$ and Δ a suitable quantization parameter (in the experiments reported in Sect.4 $N = 100$ and $\Delta = 0.15$). Function $\mathcal{Q}(\cdot)$ quantize values of $\bar{k}$ into $2N+1$ distinct classes $\{c_i\}_{i=-N}^{N}$.

To simplify notation, $v \in \mathcal{M}_i$ is synonymous with $v \in \mathcal{M}$ and $\mathcal{Q}(\bar{k}_v) = c_i$.

Definition 2.1 (Histogram of Curvature) *Given a quantization of curvature values into $2N+1$ classes $\{c_i\}_{i=-N}^{N}$, the histogram of curvature $h_{c_i}(\mathcal{M})$ of the mesh $\mathcal{M}$ is defined as:*

$$h_{c_i}(\mathcal{M}) = N_V \cdot \Pr_{v_i \in \mathcal{M}}[v_i \in \mathcal{M}_i]$$

being N_V the number of mesh vertices.

In doing so, $h_{c_i}(\mathcal{M})/N_V$ is the probability that the quantized curvature of a generic vertex of the mesh belongs to class c_i.

The correlogram of curvature is defined with respect to a predefined distance value δ. In particular, the curvature correlogram $\gamma^{(\delta)}_{c_i c_j}$ of a mesh $\mathcal{M}$ is defined as:

$$\gamma^{(\delta)}_{c_i,c_j}(\mathcal{M}) = \Pr_{v_1,v_2 \in \mathcal{M}}[(v_1 \in \mathcal{M}_{c_i}, v_2 \in \mathcal{M}_{c_j}) \mid ||v_1 - v_2|| = \delta]$$

In this way, $\gamma^{(\delta)}_{c_i,c_j}(\mathcal{M})$ is the probability that two vertices that are δ far away from each other have curvature belonging to class c_i and c_j, respectively.

Ideally, $||v_1 - v_2||$ should be the geodesic distance between vertices v_1 and v_2. However, this can be approximated with the $k-$ring distance if the mesh $\mathcal{M}$ is regular and triangulated[12].

Definition 2.2 (1-ring) *Given a generic vertex $v_i \in \mathcal{M}$, the* neighborhood *or* 1-ring *of v_i is the set:*

$$V^{v_i} = \{v_j \in \mathcal{M} : \exists e_{ij} \in E\}$$

being E the set of all mesh edges (if $e_{ij} \in E$ there is an edge that links vertices v_i and v_j).

The set V^{v_i} can be easily computed using the morphological operator *dilate* [13]:

$$V^{v_i} = dilate(v_i)$$

Through the dilate operator, the concept of *1-ring* can be used to define, recursively, generic k^{th} order neighborhood:

$$ring_k = dilate^k \cap dilate^{k-1}$$

Definition of k^{th} order neighborhood enables definition of a true metric between vertices of a mesh. This metric can be used for the purpose of computing curvature correlograms as an approximation of the usual geodesic distance (that is computationally much more demanding). According to this, we define the $k-$ring distance between two mesh vertices as $d_{ring}(v_1, v_2) = k$ if $v_2 \in ring_k(v_1)$.

Function $d_{ring}(v_1, v_2) = k$ is a true metric, in fact:

1. $d_{ring}(u, v) \geq 0$, and $d_{ring}(u, v) = 0$ if and only if $u = v$.
2. $d_{ring}(u, v) = d_{ring}(v, u)$
3. $\forall w \in \mathcal{M}\ \ d(u, v) \leq d(u, w) + d(w, v)$

Based on the $d_{ring}(\cdot)$ distance, the correlogram of curvature can be redefined as follows:

$$\gamma^{(k)}_{c_i,c_j}(\mathcal{M}) = \Pr_{v_1,v_2 \in \mathcal{M}}[(v_1 \in \mathcal{M}_{c_i}, v_2 \in \mathcal{M}_{c_j}) \,|d_{ring}(v_1, v_2) = k]$$

3. MATCHING CURVATURE CORRELOGRAMS

Several distance measures have been proposed to compute the dissimilarity of distribution functions. In order to compute the similarity between curvature correlograms of two distinct meshes $\gamma^{(k)}_{c_i,c_j}(\mathcal{M}_1)$ and $\gamma^{(k)}_{c_i,c_j}(\mathcal{M}_2)$ we experimented the following distance measures:

Minkowsky-form distance

$$d_{\mathcal{L}_p} = \left[\sum_{i,j=-N}^{N} \left| \gamma^{(k)}_{c_i,c_j}(\mathcal{M}_1) - \gamma^{(k)}_{c_i,c_j}(\mathcal{M}_2) \right|^p \right]^{1/p}$$

Histogram intersection

$$d_{HI} = 1 - \frac{\sum_{i,j=-N}^{N} \min\left(\gamma^{(k)}_{c_i,c_j}(\mathcal{M}_1), \gamma^{(k)}_{c_i,c_j}(\mathcal{M}_2)\right)}{\sum_{i,j=-N}^{N} \gamma^{(k)}_{c_i,c_j}(\mathcal{M}_2)}$$

χ^2-statistics

$$d_{\chi^2} = \sum_{i,j=-N}^{N} \frac{\left(\gamma^{(k)}_{c_i,c_j}(\mathcal{M}_1) - \gamma^{(k)}_{c_i,c_j}(\mathcal{M}_2)\right)^2}{2\left(\gamma^{(k)}_{c_i,c_j}(\mathcal{M}_1) + \gamma^{(k)}_{c_i,c_j}(\mathcal{M}_2)\right)}$$

Kullback-Leibler divergence

$$d_{KL} = \sum_{i,j=-N}^{N} \gamma^{(k)}_{c_i,c_j}(\mathcal{M}_1) log \frac{\gamma^{(k)}_{c_i,c_j}(\mathcal{M}_1)}{\gamma^{(k)}_{c_i,c_j}(\mathcal{M}_2)}$$

Using a groundtruth database, the above distance measures have been compared in terms of precision and recall figures. Results of this analysis (not reported in this paper for lack of space) suggest that the best performance is achieved by using χ^2-statistics to measure the distance between curvature correlograms.

4. EXPERIMENTAL RESULTS

Approximately 300 models were collected to build the test database. These comprise four classes of models: taken from the web, manually authored (with a 3D CAD software), high quality 3D scans from the De Espona 3D Models Encyclopedia[1], and variations of the previous three classes (obtained through deformation or application of noise, which caused points surface to be moved from their original locations). Content descriptors, in the form of curvature correlograms, were then extracted from database objects and added to the index.

[1] `http://www.deespona.com`

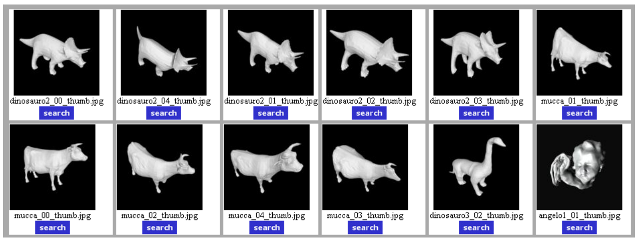

Fig. 1. A retrieval example, using the model of a dinosaur as the query. Other models of dinosaurs were retrieved first, followed by models of other objects which display similar features.

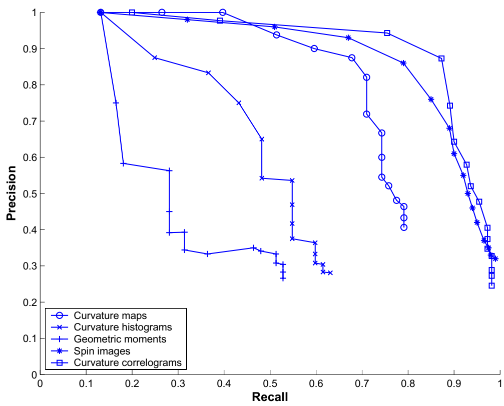

Fig. 2. The average Precision-Recall curve over a given set of queries shows an improved performance w.r.t. to four alternative approaches.

Fig.1 shows a retrieval example where the model of a dinosaur is used as a query. The result set displays all models of similar animals in the first positions. These animals all share some major features such as four legs, a tail and two horns.

In Fig. 2, the precision-recall curve of the proposed approach is compared with the curve of alternative approaches. In particular approaches based on 3D geometric moments [7], curvature histograms [15], curvature maps [8] and spin images [9]. The proposed solution shows an improved performance w.r.t. to all the four alternative approaches.

5. CONCLUSIONS AND FUTURE WORK

In this paper we have presented an approach to retrieval by content of 3D objects based on curvature correlograms. The main advantage of correlograms relates to their ability to encode not only distribution of features but also their arrangement on the object surface. Experimental results have shown that the proposed solution is well suited for the purpose of retrieval. Furthermore, results showed that the approach performs better than previous approaches to content-based retrieval of 3D objects. Future work will address extension of correlograms to deal with multiresolution descriptors as well as the definition of suitable distance measures to cope with retrieval by object parts.

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