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Content-based image retrieval tools and techniques

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Content-Based Image Retrieval Tools and Techniques

In the beginning was an image.

To my mother
who inspired me
to develop intellectually

Contents

6 Signature Similarity

6.1 Introduction

As we have explained it in sect. 3.8 the introduction of an appropriate signature is a challenging problem. When a decision on the choice of image signatures has been made, how to use them for accurate image retrieval is the next concern. There is a large number of fundamentally different solutions proposed in recent years. Some of the key motivating factors behind the design of the proposed image similarity measures can be summarized as follows:

- agreement with semantics;
- robustness to noise (invariant to perturbations);
- computational efficiency (ability to work in real time and in large scale);
- invariance to background (allowing region-based querying); and
- local linearity (i.e., following triangle inequality in a neighbourhood).

The various techniques can be grouped according to design philosophy as follows:

- treating features as vectors, non-vector representations, or ensembles;
- using region-based similarity, global similarity, or a combination of both;
- computing similarities over linear space or nonlinear manifold;
- considering the role played by image segments in similarity computation;
- using stochastic, fuzzy, or deterministic similarity measures;
- use of supervised, semi-supervised, or unsupervised learning.

Some of those methods have been discussed in [41], but here, we focus on some of the more recent approaches to image similarity computation.

As we have observed in sect. 5.2.1, there are many metrics fulfilling all metric requirements. However, in real life the symmetry is questionable, for example, the way up a hill and down a hill takes different time. A similar situation is when we compare images. We can imagine various criteria, for instance, the number of particular elements or segments which constitute a query. Hence, when we select as a query an image among the previous matching images, we obtain a different set of matching images because the symmetry is incomplete.

In such a situation a quasi-metric may be needed. A quasi-metric is defined as a function that satisfies the previously mentioned axioms for a metric without symmetry:

$$d(x,y) \neq d(y,x). \quad (6.1)$$

This notion is more often used in practice than in mathematics, and that is why it is sometimes called a semi-metrics [163].

6.2 Hausdorff Distance

As we have mentioned in the previous sections (3.8, 5.2.1 and 5.5), a feature value can be global, i.e. taking in to account all the pixels in the image, and local only for some segments.

An image signature can be seen as the form of a weighted set of feature vectors $\{(z_1, p_1), (z_2, p_2),...,(z_n, p_n)\}$, where z_i's are the feature vectors and p_i's are the corresponding weights assigned to them. Let us denote two signatures by:

$$I_m = \{(z_1^{(m)}, p_1^{(m)}), (z_2^{(m)}, p_2^{(m)}),...,(z_{n_m}^{(m)}, p_{n_m}^{(m)})\}, \quad m = 1,2. \quad (6.2)$$

A natural approach to defining a region-based similarity measure is to match $z_i^{(1)}$'s with $z_i^{(2)}$'s and then to combine the distances between these vectors as a distance between sets of vectors [164], which is not as intuitive as between individual vectors.

One approach to the matching images I_1 and I_2 [164] is an assignment of a weight $s_{i,j}$ to every pair $z_i^{(1)}$ and $z_j^{(2)}$, $1 \leq i \leq n_1$, $1 \leq j \leq n_2$, so that the weight $s_{i,j}$ indicates the significance of associating $z_i^{(1)}$ with $z_j^{(2)}$. One motivation for the soft matching is to reduce its impact on retrieval of inaccurate segmentation. The weights are subject to constraints, the most common ones being $\sum_i s_{i,j} = p_j^{(2)}$ and $\sum_j s_{i,j} = p_i^{(1)}$. Once the weights are determined, the distance between I_1 and I_2 is aggregated from the pair-wise distances between individual vectors.

Specifically:

$$D(I_1, I_2) = \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} s_{i,j}\, d(z_i^{(1)}, z_j^{(2)}) \quad (6.3)$$

where the vector distance $d(\cdot,)$ can be defined in diverse ways depending on the system.

One heuristic to decide the matching weights $s_{i,j}$ for the pair $(z_i^{(1)}, z_j^{(2)})$ is to seek $s_{i,j}$'s, such that $D(I_1, I_2)$ in eq. (6.3) is minimized, subject to certain constraints on $s_{i,j}$. Suppose $\sum_i p_i^{(1)} = 1$ and $\sum_j p_j^{(2)} = 1$. This can always be made true by the normalization, as long as there is no attempt to assign one image an overall higher signficance than the other.

In practice, $p_i^{(1)\prime}$s (or $p_j^{(2)\prime}$s) often correspond to probabilities and automatically yield unit sum. Since $p_i^{(1)}$ indicates the significance of region $z_i^{(1)}$ and $\sum_j s_{i,j}$ reflects the total influence of $z_i^{(1)}$ in the calculation of $D(I_1, I_2)$, it is natural to require $\sum_j s_{i,j} = p_i^{(1)}$ for all i, and similarly $\sum_i s_{i,j} = p_j^{(2)}$, for all j. Additionally, we have the basic requirement $s_{i,j} \geq 0$ for all i,j. The definition of the distance is thus:

$$D(I_1, I_2) = \min_{s_{i,j}} \sum_{i=1}^{n_1} \sum_{j=1}^{n2} s_{i,j}\, d(z_i^{(1)}, z_j^{(2)}), \tag{6.4}$$

This distance is precisely the Mallows distance in the case of discrete distributions [165], [166].

Other matching methods include the Hausdorff distance, which is asymmetric. We present it here for sets and show how to make more general for vectors.

Definition 6.1. (Hausdorff metric) [167]

Let (X,ρ) be a metric space and $C(X) \subseteq X$ be a space of non-empty, closed and bounded subsets of X. Let $N_\varepsilon(A) = \bigcup_{x \in A} B_\varepsilon(x)$ be the cover of $A \in X$ by open ε-balls $B_\varepsilon(x) = \{y \in X : \rho(x,y) < \varepsilon\}$, where A, B are two compact subsets of metric space X. Since $B_\varepsilon(x)$ is a neighbourhood of x, then $N_\varepsilon(A)$ is a neighbourhood of A according to the definition of natural topology in metric spaces. The Hausdorff distance between A and B is defined as the smallest ε-neighbourhood of A which covers B and the other way round (see Fig. 6.1). On the other hand, the direct Hausdorff distance between A and B, $d_H^{\triangleright}(A,B)$ can be expressed as the maximum taken over from the collection of minimum distances between elements of sets A and B.

In the case of feature vectors, where every $z_i^{(1)}$ is matched to its closest vector in I_2, say $z_{i'}^{(2)}$, the distance between I_1 and I_2 is the maximum among all $\mathrm{d}(z_i^{(1)}, z_{i'}^{(2)})$. The Hausdorff distance by default is asymmetrical, hence in order to make it symmetrical additional computing must be done: the distance with the reversed role of I_1 and I_2 needs to be calculated and the larger of the two distances is selected:

$$D_H(I_1, I_2) = \max\left\{\max_i \min_j \mathrm{d}\left(z_i^{(1)}, z_j^{(2)}\right), \max_j \min_i \mathrm{d}\left(z_j^{(2)}, z_i^{(1)}\right)\right\} \tag{6.5}$$

The Hausdorff distance is used for image retrieval in **[168]**.

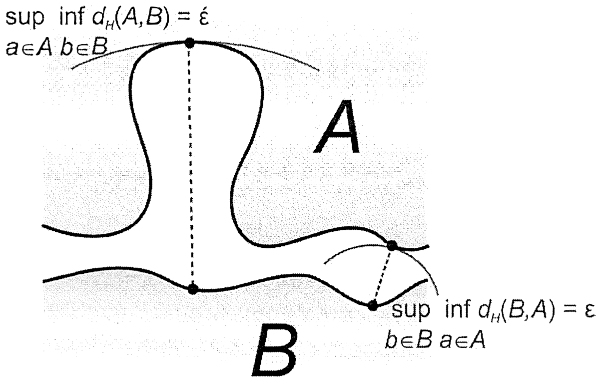


Fig. 6.1. Illustration of the asymmetric Hausdorff distance between sets A and B: $d_H(A,B) = \acute{\varepsilon}$ and sets B and A: $d_H(B,A) = \varepsilon$.

6.3 Signature Quadratic Form Distance

From eq. (6.2) we can notice that carrying out feature clustering individually for each data object reflects aggregation of feature distribution in a better way than any feature histogram. However, feature histograms are a special case of feature signatures whose centroids stay the same for the whole database and the information about objects is reflected only via weights, which results in a limitation of object representation.

Definition 6.2 (Feature signature [169])

Let $FS \subseteq R^k$ be a feature space and $C = C_1,...,C_k$ be a local clustering of the features $f_1,\dots,f_n \in FS$ of object o_{ij}. Then a feature signature S^o of length M^i can be defined as a set of tuples from a $FS \times R^+$, such as:

$$S^o = \{\langle c_k^o, w_k^o\rangle, k = 1, \dots, M\}. \tag{6.6}$$

where: $c_k^o = \frac{\sum_{f \in c_k} f}{|c_k|}$ is a centroid of similar objects o_{ij} of image I_i and $w_k^o = \frac{|c_k|}{n}$ is its weight.

It means that a feature signature S^o of object o_{ij} is a set of centroids $c_k^o \in FS$ with the corresponding weights $w_k^o \in R^+$ (see Fig. 6.2 (a)).

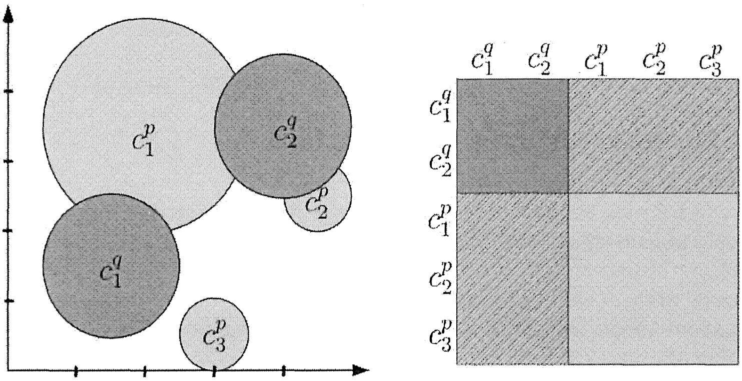
By this approach, Beecks et al. [169] aggregated the objects' location in the feature space which is substituted only by grouping similar feature values in signature and histogram form. They proposed seven basic features: two coordinates, three components of colour and two texture descriptors.

Definition 6.3 (Signature Quadratic Form Distance [169])

If $S^o = \{\langle c_k^o, w_k^o \rangle, k = 1, \dots, M\}$ and $S^q = \{\langle c_k^q, w_k^q \rangle, k = 1, \dots, N\}$ are two feature signatures, then the Signature Quadratic Form Distance (SQFD) between S^o and S^q is defined as:

$$\mathrm{SQFD}(S^o, S^q) = \sqrt{(w_o | - w_q) A (w_o | - w_q)^T} \tag{6.7}$$

where: $A \in R^{(M+N)\times(M+N)}$ is the similarity matrix, $w_q = (w_1^q, \dots, w_m^q)$ and $w_o = (w_1^o, \dots, w_n^o)$ are weight vectors and $(w_o | - w_q) = (w_1^o, \dots, w_n^o, -w_1^q, \dots, -w_m^q)$.



(a) (b)

Fig. 6.2 (a) Two feature signatures with their centroids and weights. (b) The illustration of the structure of similarity matrix A for two signatures S^o and S^q, according to Beeks et al. [169].

The similarity matrix **A** can be constructed assuming that there exists a similarity function $f: FS \times FS \rightarrow R$. The $a_{k,l}$ components of **A** are calculated as follows:

$$a_{k,l} = f(c_k^o, c_l^q) = \frac{1}{1 + d(c_k^o, c_l^q)} = \frac{1}{1 + \left[\left(c_{k,x}^o - c_{l,x}^q\right)^2 + \left(c_{k,y}^o - c_{l,y}^q\right)^2\right]} \tag{6.8}$$

where: $k, l = 1, \dots, N+M$.

Fig. 6.3 and Fig. 6.4 present matching for two queries created by the user in the Hybrid Sematic System (HSS) (see sect. 9.9), computed according to the signature quadratic form distance (cf. (6.7)).

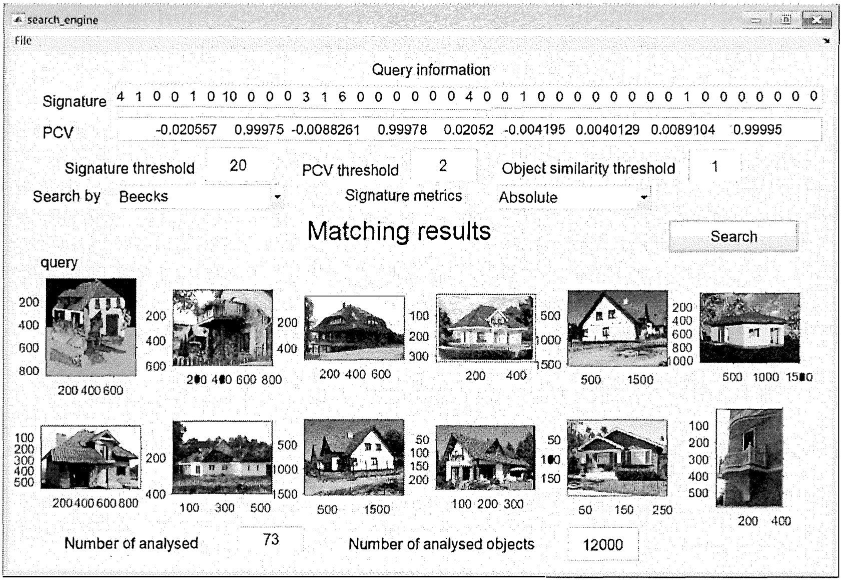


Fig. 6.3 Matching results for signature quadratic form distance for query 1.

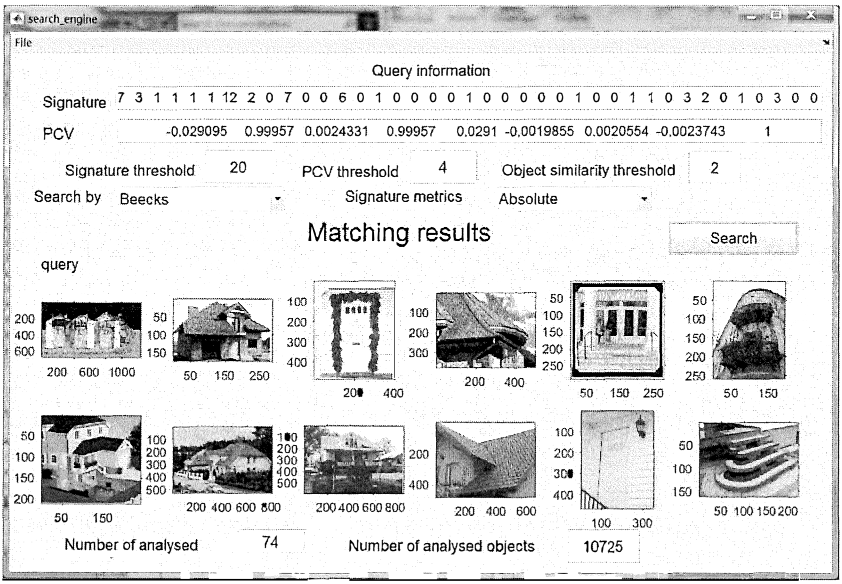


Fig. 6.4 Matching results for signature quadratic form distance for query 2.

6.4 Asymmetrical Signature Similarity in the Hybrid Semantic System

In the hybrid sematic system [170], at the first stage, objects o_{ij} are extracted from an image I_i based on low-level features (as it has been described in sect.4.2.4). These features are used for object classification. Additionally, the objects' mutual spatial relationship is calculated based on the centroid locations and angles between vectors connecting them, with an algorithm proposed by Chang and Wu [161] and later modified by Guru and Punitha [162], to determine the first three principal component vectors (PCV_{oi}, i=1,…,3 for each object o_{ij}). Spatial object location in an image is used as the global feature [52] (compare sect. 5.5).

Definition 6.4 (Image signature [170])

Let the query be an image I_q (cf. (5.22)), such as $I_q = \{o_{q1}, o_{q2}, \ldots, o_{qn}\}$, where o_{ij} are objects. An image in the database is denoted as I_b, $I_b = \{o_{b1}, o_{b2}, \ldots, o_{bm}\}$. Let us assume that in the database there are, in total, M classes of the objects marked as $L_1, L_2, \ldots, L_M$. Then, as the image signature I_i we denote the following vector:

$$\text{Signature}(I_i) = [\text{nobc}_{i1}, \text{nobc}_{i2}, \ldots, \text{nobc}_{iM}] \qquad (6.9)$$

where: nobc_{ik} are the number of objects o_{ij} of class L_k segmented from an image I_i. Note that the length of a signature is always the same and is equal to M.

Asymmetry is one of the most controversial properties of similarity. Like the Kullback-Leibler (K-L) divergence (see eq. (3.58)). and the Hausdorff distance our signature similarity is asymmetric. In order to answer the query I_q, we compare it with each image I_b from the database in the following way. A query image is obtained from the GUI, where the user constructs their own image from selected DB objects. First of all, we determine a similarity measure sim_{sgn} between the signatures of query I_q and image I_b:

$$\text{sim}_{\text{sgn}}(I_q, I_b) = \sum_i (\text{nob}_{qi} - \text{nob}_{bi}) \qquad (6.10)$$

computing it as an equivalent of the Hamming distance between two vectors of their signatures (cf. (6.9)), such that $\text{sim}_{\text{sgn}} \geq 0$ and $\max_i(\text{nob}_{qi} - \text{nob}_{bi}) \leq \text{thr}$, thr is the limitation of the quantity of elements of a particular class by which I_q and I_b can differ. It means that we select from the DB images with objects in the same classes as the query. The above comparison is asymmetric because if we interchange the query and the image, we obtain a negative similarity value, that is:

$$\text{sim}_{\text{sgn}}(I_q, I_b) = -\,\text{sim}_{\text{sgn}}(I_b, I_q).$$

Then, the condition of non-negativity of similarity is incomplete. This fact is crucial from the semantic matching point of view because the human brain recognizes things in context with others.

Beecks et al. proposed only seven basic features, whereas we offered 45 features for a particular object, for example: moments of inertia and Zernike's moments [104].

In our adaptation of their method [171], a number of objects of a particular class were interpreted as weights. Object centroids represent locations of real, early segmented objects in the image space. Here, class centroids are situated in the geometrical centre among particular object centroids. We also use different methods to determine the similarity in these two approaches.

In our approach, there is the same number of classes for each image signature (N=M), hence we decided to assume the length of vectors w_q and w_o equal to M which implies the size of a square matrix $\mathbf{A}_{[M \times M]}$. Then the signature form distance (6.7) can be simplified to the form:

$$\mathrm{SQFD}(S^o, S^q) = \sqrt{w_o A\, w_q{}^T} \tag{6.11}$$

and $a_{k,l}$ components are computed only for $k,l = 1,\ldots, M$, according to (6.8). Here, in Def. 2.3 and in our approach, S^q means a query signature, whereas S^o means image signatures in the database. The signature similarity, computed according to SQFD (cf. (6.11)), gives more information than the one computed according to $\mathrm{sim}_{\mathrm{sgn}}$ (cf. (6.10)) which is seen in the results.

Results are presented in Table 9.1 and Table 9.2 in the sect. 9.9 where the search engine for the Hybrid Semantic System is described in detail.

6.5 Other Signature Similarities

The above-mentioned methods have been used so far, however, it has been observed lately that it is too ambitious to expect a single similarity measure to produce an effective, perceptually meaningful ranking of images or objects. As an alternative, attempts have been made to augment the effort with learning-based techniques.

Automatic learning of image similarity measures with the help of contextual information has been explored in Wu et al. [172]. In the case when a valid pair-wise image similarity metric exists despite the absence of an explicit vectored representation in some metric space, *anchoring* can be used for ranking images [173]. Anchoring involves choosing a set of representative *vantage* images, and using the similarity measure to map an image into a vector. Suppose there exists a valid metric $d(F_i, F_j)$ between each image pair, and a chosen set of K vantage images $\{A_1,\ldots, A_K\}$. A *vantage space transformation* $V_A{:}F \rightarrow R^K$ then maps each image F_i in the database with N objects to a vectored representation $V_A(F_i)$ as follows:

$$V_A(F_i) = < d(F_i, A_1), \ldots, d(F_i, A_K) >, \ \forall\ 1 \leq i \leq N \qquad (6.12)$$

With the resultant vector embedding, and after similarly mapping a query image in the same space, standard ranking methods may be applied for retrieval. When images are represented as ensembles of feature vectors, or underlying distributions of the low level features, visual similarity can be ascertained by means of nonparametric tests such as Wald-Wolfowitz and K-L divergence. When images are conceived as bags of feature vectors corresponding to regions, multiple-instance multi-label learning (MIML) can be used for similarity computation [174].

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