

## Research Article

# Density-Based 3D Shape Descriptors

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We propose a novel probabilistic framework for the extraction of density-based 3D shape descriptors using kernel density estimation. Our descriptors are derived from the probability density functions (pdf) of local surface features characterizing the 3D object geometry. Assuming that the shape of the 3D object is represented as a mesh consisting of triangles with arbitrary size and shape, we provide efficient means to approximate the moments of geometric features on a triangle basis. Our framework produces a number of 3D shape descriptors that prove to be quite discriminative in retrieval applications. We test our descriptors and compare them with several other histogram-based methods on two 3D model databases, Princeton Shape Benchmark and Sculpteur, which are fundamentally different in semantic content and mesh quality. Experimental results show that our methodology not only improves the performance of existing descriptors, but also provides a rigorous framework to advance and to test new ones.

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## 1. INTRODUCTION

The use of 3D models is becoming increasingly more commonplace with their distribution on the Internet and with the availability of 3D scanners. Many fields are focused on 3D object models: computer graphics, computer-aided design, medical imaging, molecular analysis, cultural heritage in virtual environments, movie industry, military target detection, or industrial quality control to name a few. Efficient organization and access to these databases demand effective tools for indexing, categorization, classification, and representation of 3D objects. All these database activities hinge on the development of 3D object similarity measures. There are two paradigms for 3D object database operations and design of similarity measures, namely, the feature vector approach and the nonfeature vector approach [1, 2]. The feature vector paradigm aims at obtaining numerical values of certain shape descriptors and measuring the distances between these vectors. A typical example of nonfeature-based approach is to describe the object as a graph and then use graph similarity metrics. In this work, we follow the feature vector paradigm, and furthermore we limit our scope to the subclass of histogram-based descriptors.

Representations used for shape matching are often referred to as 3D shape descriptors and they usually differ

substantially from those intended for 3D object rendering and visualization [3]. Shape descriptors aim at encoding geometrical and topological properties of an object in a discriminative and compact manner. The diversity of shape descriptors range from 3D moments to shape distributions, from spherical harmonics to ray-based sampling, from point clouds to voxelized volume transforms [1, 2, 4–7]. In this work, inspired from histogram-based 3D shape descriptors [8–12], we propose a density-based approach that applies to local geometrical features of arbitrary dimension. Our interest in histogram-based 3D shape descriptors stems from their generality and their simplicity. They are global descriptors based on sets of local measurements and they have been shown to be effective in classifying shapes into broad categories [2]. Our objective is to show that, in addition to their categorization capability, they have also satisfactory retrieval performance.

Any histogram-based 3D shape descriptor must face the problem of estimating the histogram from any given mesh composed of triangles usually with arbitrary forms and sizes. In the previous histogram-based approaches, the surface samples are either chosen as the centers of gravity of the triangles or obtained by randomly sampling several points from the surface. A single sample from each triangle may not adequately represent the mesh. The random sampling of the

surface may compensate for the nonuniform distribution of triangles, provided that a sizeable number of surface points is taken. Although the random sampling approach proves to be useful for computing histograms of scalar features [10], it is not practical in the multidimensional case due to the curse of dimensionality: the number of samples required to fill in the multivariate histogram bins increases exponentially as dimensionality increases [13], resulting in a significant extra computational load which is not affordable for most applications such as retrieval.

Our density-based framework makes a more effective use of each triangle and also takes care of the nonuniformity of their areas and orientations without resorting to expensive random sampling. First, we do not use samples but exploit the information in the whole triangle area using an integration scheme, as described in Section 3.3. Second, we resort to nonparametric kernel density estimation (KDE) with rule-based bandwidth parameter assignment [13, 14]. In other words, local geometric information emanating from each mesh triangle contributes to the geometric feature density by the intermediary of a kernel. Thus local evidences about surface shape are accumulated at targeted density points to result in a global shape description. Third, we use a Gaussian kernel. Since the Gaussian density is completely determined by its first two moments, we only need to estimate the mean and the variance of the feature for each triangle. For certain cases, these moments can be approximated very accurately by making use of the geometry of a triangle in 3D space. The choice of Gaussian kernel brings in the additional advantage of alleviating the computational burden of calculating large sums of Gaussians, as occur in the proposed set of descriptors, by enabling the use of the efficient fast Gauss transform (FGT) [15, 16]. Thus the main contribution of our work is to propose an analytical framework for the extraction of 3D descriptors from local surface features that characterize the object geometry. This framework computes probability densities of local features instead of their conventional histograms. Here, we interpret histograms and densities in a broad sense: any descriptor that uses an accumulator scheme of measured quantities qualifies as a histogram-based descriptor. As a byproduct, we also introduce some novel local features.

The rest of the paper is structured as follows. In Section 2, we provide an overview of histogram-based 3D shape descriptors. Section 3 introduces the local geometric features we have considered and describes the KDE-based computational framework. In Section 4, we illustrate the retrieval performance of our method in comparison to other equivalent or similar histogram-based descriptors [8–12]. In Section 5, we draw conclusions and discuss further directions in density-based 3D shape descriptors.

## 2. PREVIOUS WORK ON 3D SHAPE DESCRIPTORS

There are two main paradigms of 3D shape description, namely, graph-based and vector-based. Graph-based representations are more elaborate and complex, harder to obtain, but represent shape properties in a more faithful and

intuitive manner. Shock graphs [17], multiresolution Reeb graphs [6, 18, 19], and skeletal graphs [20] are methods that fall in this category. However, they do not generalize easily and hence they are not very convenient to use in unsupervised learning, for example, to search for natural shape classes in a database. Vector-based representations, on the other hand, are more easily computed. Although they do not necessarily conduce to plausible topological visualizations, they can be naturally employed in both supervised and unsupervised classification tasks. Typical vector-based representations are extended Gaussian images [8, 9], cord and angle histograms [11], 3D shape histograms [21], spherical harmonics [7, 22–24], and shape distributions [10]. In this work, we are exclusively interested in histogram-based 3D shape descriptors that constitute a particular branch of vector-based representations. In the following, we provide a brief overview of histogram-based descriptors. References [1, 2, 4] provide also excellent surveys.

In [11], Paquet and Rioux present *cord and angle histograms* for matching 3D objects. A “cord,” which is actually a ray, joins the barycenter of the mesh with a triangle center. The histograms of the length and of the angles of these rays (with respect to a reference frame) are used as the 3D shape descriptors. Although automatic determination of a canonical reference frame for 3D meshes is still not totally solved [7], the common practice is to obtain the eigendecomposition of the covariance matrix of the surface points. The covariance matrix itself can be computed using the mesh vertices, the triangle centers, or in a “continuous” way as described in [7]. The resulting eigenvectors, which are the orthogonal directions along which the mesh has maximal spread, are taken as a reference frame. Notice that the eigendirections may not necessarily correspond to the “natural” pose of the object; however, they can serve as a canonical reference frame. In conclusion, Paquet and Rioux [11] consider the shape descriptors consisting of the ray length and the relative ray angles with respect to the largest two eigenvectors. One shortcoming of all such approaches that reduce the triangles to their center points is that they do not take into consideration the size and shape of the mesh triangles. First, because triangles of any size have equal weight in the final shape distribution; second, because the triangle shapes can be arbitrary, so that the center may not represent adequately the impact of the triangle on the shape distribution.

In the *shape distributions* approach, Osada et al. [10] use a collection of shape functions, which are geometrical quantities estimated by a random sampling of the surface of the 3D object. Their shape functions are defined as the distance of surface points to the center of mass of the model (D1), the distance between two surface points (D2), the area of the triangle defined by three surface points (D3), the volume of the tetrahedron defined by four surface points (D4), and so on. The descriptors of the object are then defined as the histograms of these shape functions. The randomization of the surface sampling process improves the estimation over Paquet and Rioux’s approach [11], since a more representative and dense set of surface points is used. Obviously, the histogram accuracy can be controlled with the sample size.

TABLE 1: Invariance properties of histogram-based 3D shape descriptors.

Descriptor	Translation invariance	Rotation invariance	Scale invariance
<i>Cord histogram</i> [11]	No	Yes	No
<i>Angle histogram</i> [11]	No	No	Yes
<i>D1-distribution</i> [10]	No	Yes	No
<i>D2-distribution</i> [10]	Yes	Yes	No
<i>Shape histogram (shells)</i> [21]	No	Yes	No
<i>Shape histogram (sectors)</i> [21]	No	No	No
<i>EGI</i> [8]	Yes	No	No
<i>CEGI</i> [9]	No	No	No
<i>3DHT</i> [12]	No	No	No

Ankerst et al. use *shape histograms* for the purpose of molecular surface analysis [21]. A shape histogram is defined by partitioning the 3D space into concentric shells and sectors around the center of mass of a 3D model. The histogram is constructed by accumulating the surface points in the bins (in the form of shells, sectors, or both) based on a nearest-neighbor rule. Ankerst et al. [21] illustrate the shortcomings of Euclidean distance to compare two shape histograms and make use of a Mahalanobis-like quadratic distance measure taking into account the distances between histogram bins.

*Extended Gaussian images* (EGI), introduced by Horn [8], form another class of histogram-based 3D shape descriptors. An EGI consists of a spherical histogram with bins indexed by  $(\theta_j, \varphi_k)$ , where each bin corresponds to some quantum of the spherical azimuth and elevation angles  $(\theta, \varphi)$  in the range  $0 \leq \theta < 2\pi$  and  $0 \leq \varphi < \pi$ . The histogram bins accumulate the count of the spherical angles of the surface normal per triangle, usually weighted by the triangle area. Kang and Ikeuchi have extended the EGI approach by considering the normal distances of the triangles to the origin [9]. Accordingly, each histogram bin accumulates a complex number whose magnitude and phase are the area of the triangle and its signed distance to the origin, respectively. The resulting 3D shape descriptor is called complex extended Gaussian images (CEGI) [9].

In [12], Zaharia and Prêteux present the *3D Hough transform descriptor* (3DHT) as a histogram constructed by accumulating surface points over planes in 3D space. Each triangle of the mesh contributes to each plane with a weight equal to the projected area of the triangle on the plane but only if the scalar product between their normals is higher than a given threshold. Although we have not encountered in the literature a direct comparison between 3DHT and EGI, 3DHT can be considered as a generalized version of EGI, where concentric spherical shells of different radii are constructed around the object's center of mass. One can consequently conjecture that the 3DHT descriptor captures the shape information better than the EGI descriptor, as will be shown experimentally in Section 4.

An important property of a 3D shape descriptor is its invariance to similarity transformations, that is, translation (T), rotation (R), and scale (S) [1, 2, 4, 7]. In Table 1, we

summarize invariance properties of the histogram-based shape descriptors discussed above.

### 3. THE PROPOSED FRAMEWORK FOR DENSITY-BASED DESCRIPTORS

#### 3.1. Local geometric features

We assume that each 3D shape is represented as a triangular mesh and that its center of mass coincides with the origin of the coordinate system. In what follows, capital italic letter  $P$  stands for a point in 3D, a small case boldface letter  $\mathbf{p} = (p_x, p_y, p_z)$  for its vector representation,  $\hat{\mathbf{n}}_P = (\hat{n}_{P,x}, \hat{n}_{P,y}, \hat{n}_{P,z})$  for the unit surface normal vector at  $P$  when  $P$  belongs to a surface  $\mathcal{M} \subset \mathbb{R}^3$ , and  $\langle \cdot, \cdot \rangle$  for the usual dot product.

We define a local geometric feature as a mapping  $S$  from the points of a surface  $\mathcal{M} \subset \mathbb{R}^3$  into a  $d$ -dimensional space, generally a subspace of  $\mathbb{R}^d$ . Each dimension of this space corresponds to a specific geometric property that can be calculated at each point of the surface. For example, the distance of a surface point to the center of the 3D shape is a one-dimensional ( $d = 1$ ) geometric feature, while the mesh triangle normal  $\hat{\mathbf{n}}_P$  is a three-dimensional feature vector ( $d = 3$ ). In this work, we consider three different multidimensional local geometric features that we describe in the sequel.

The *radial feature*  $S_r$  at a point  $P$  is a 4-tuple defined as

$$\begin{aligned}
 r_P &\triangleq \sqrt{p_x^2 + p_y^2 + p_z^2}, \\
 \hat{r}_{P,x} &\triangleq \frac{p_x}{r_P}, \\
 \hat{r}_{P,y} &\triangleq \frac{p_y}{r_P}, \\
 \hat{r}_{P,z} &\triangleq \frac{p_z}{r_P}.
 \end{aligned}
 \tag{1}$$

Accordingly,  $S_r$  consists of a magnitude component  $r_P$  measuring the distance of the point  $P$  to the origin, and a direction component  $\hat{\mathbf{r}}_P \triangleq (\hat{r}_{P,x}, \hat{r}_{P,y}, \hat{r}_{P,z})$  that gives the orientation of the point  $P$  (see Figure 1). Observe that we can write  $S_r$  also as  $S_r(P) = (r_P, \hat{\mathbf{r}}_P)$ . The direction component  $\hat{\mathbf{r}}_P$  is a three-dimensional vector with unit norm; hence it lies on the unit sphere.

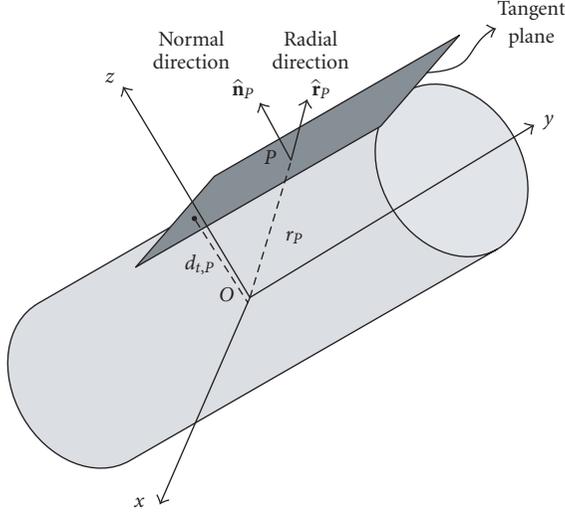


FIGURE 1: Radial and normal directions of a surface point.

The *tangent plane-based feature*  $S_t$  at a point  $P$  is a 4-tuple defined as

$$S_t(P) = (d_{t,P}, \hat{n}_{P,x}, \hat{n}_{P,y}, \hat{n}_{P,z}) \quad \text{with } d_{t,P} \triangleq r_P |\langle \hat{r}_P, \hat{n}_P \rangle|. \quad (2)$$

Similar to the  $S_r$  feature,  $S_t$  has a magnitude component  $d_{t,P}$ , which stands for the distance of the tangent plane at  $P$  to the origin, and a direction component  $\hat{n}_P = (\hat{n}_{P,x}, \hat{n}_{P,y}, \hat{n}_{P,z})$  (see Figure 1). Thus, we may write  $S_t(P) = (d_{t,P}, \hat{n}_P)$ . The normal  $\hat{n}_P$  is a unit norm vector by definition and lies on the unit sphere.

The *cross-product feature*  $S_c$  aims at encoding the relationship between the former two features, namely, the radial feature  $S_r$  and the tangent plane-based feature  $S_t$ . To this end, we define  $S_c$  at a point  $P$  as

$$S_c(P) \triangleq (r_P, c_{P,x}, c_{P,y}, c_{P,z}) \triangleq (r_P, \mathbf{c}_P) \quad \text{with } \mathbf{c}_P \triangleq \hat{r}_P \times \hat{n}_P. \quad (3)$$

In much the same way as in  $S_r$  and  $S_t$ ,  $S_c$  is decoupled into a magnitude component  $r_P$  and a direction component  $\mathbf{c}_P$ . Notice, however, that  $\mathbf{c}_P$  is not a unit-norm vector unless the angle between the radial direction  $\hat{r}_P$  and the normal direction  $\hat{n}_P$  is  $\pi/2$ . Both  $\hat{r}_P$  and  $\hat{n}_P$  being unit norm vectors, the norm of  $\mathbf{c}_P$  is lower than or equal to unity and it lies inside the unit ball.

The local geometric features presented above and their invariance properties are summarized in Table 2.

### 3.2. Kernel density estimation

Given a set of observations  $\{s_k\}_{k=1}^K$  for a random variable (scalar or vector)  $S$ , the kernel approach to estimate the probability density of  $S$  is formulated in its most general form as

$$f_S(s) = \sum_{k=1}^K w_k |H_k|^{-1} \mathcal{K}(H_k^{-1}(s - s_k)), \quad (4)$$

TABLE 2: Local geometric features and their invariance properties (assuming that the barycenter of the surface  $\mathcal{M}$  is at the origin).

Feature	Component-wise invariance	Overall invariance
Radial $S_r$	Magnitude $r_P$ : rotation Direction $\hat{r}_P$ : scale	None
Tangent plane $S_t$	Magnitude $d_{t,P}$ : rotation Direction $\hat{n}_P$ : scale	None
Cross-product $S_c$	Magnitude $r_P$ : rotation Direction $\mathbf{c}_P$ : scale	None

where  $\mathcal{K} : \mathbb{R}^d \rightarrow \mathbb{R}$  is a kernel function,  $H_k$  is a  $d \times d$  matrix composed of a set of design parameters called *bandwidth parameters* (smoothing parameters or scale parameters) for the  $k$ th observation, and  $w_k$  is the importance weight associated with the  $k$ th observation. The contribution of each data point  $s_k$  to the density function  $f_S(s)$  at a target point  $s$  is computed through the kernel function  $\mathcal{K}$  scaled by the matrix  $H_k$  and the weight  $w_k$ . Thus KDE involves a data set  $\{s_k\}_{k=1}^K$  with the associated set of importance weights  $\{w_k\}_{k=1}^K$ , the choice of a kernel function  $\mathcal{K}$  and the setting of bandwidth parameters  $\{H_k\}_{k=1}^K$ .

We compute the probability density values of a certain local geometric feature  $S$  from a set of observations  $\{s_k\}_{k=1}^K$ . We assume that the 3D shape is represented as a triangular mesh consisting of  $K$  triangles. Thus we can obtain an observation  $s_k$  from each of the triangles in the mesh, as will be explained in Section 3.3. Since, in general, the mesh is made up of nonuniformly sized triangles, the data should be weighted accordingly. A natural choice for the importance weight  $w_k$  of a data point  $s_k$  is the ratio of the  $k$ th triangle area to the total surface area, yielding  $\sum_{k=1}^K w_k = 1$ . It is known that the particular functional form of the kernel does not significantly affect the accuracy of the estimator [14]. The Gaussian kernel has become a popular choice, first because it lends itself more easily to asymptotic error analysis [14]; and second, for the existence of efficient algorithms to calculate large sums of Gaussians, as the fast Gauss transform (FGT) already mentioned in the introduction [15, 16]. Actually, FGT is the dominant reason why we choose the Gaussian kernel since computational efficiency is an important requirement for 3D object retrieval [1, 2] (see Section 3.6 for details).

The setting of the bandwidth parameters  $\{H_k\}_{k=1}^K$  is critical for an accurate kernel density estimation [14, 25]. For the Gaussian kernel, the bandwidth matrix  $H_k$  simply corresponds to the feature covariance matrix. For setting/estimating the bandwidth parameters, there exist several guidelines and computational methods with varying complexity [14, 25]. We discuss different alternatives in Section 3.4. The probability density function  $f_S(s)$ , when computed over predefined target points using (4), results in the shape descriptor sought for a given triangular mesh. The methodology that we employ to choose the target points for each specific feature is explained in Section 3.5.

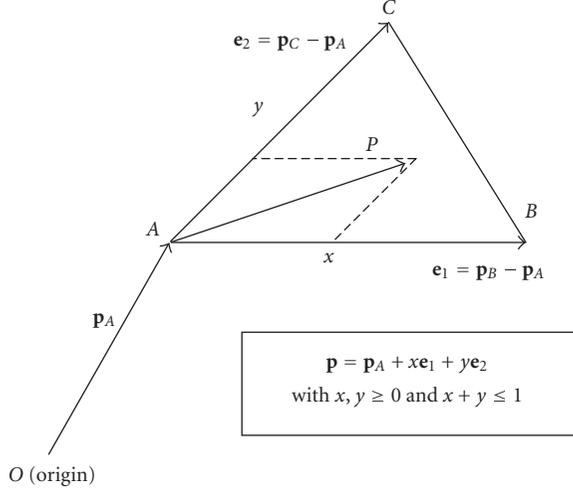


FIGURE 2: A local basis for a triangle in 3D.

### 3.3. Feature calculation

Given a  $d$ -dimensional local feature  $S = (S_1, \dots, S_d)$ , the observation  $s_k$  can be obtained from the mesh triangle  $T_k$  by evaluating the value of  $S$  at the barycenter of the triangle. However, the mesh triangles having in general arbitrary shapes, the feature value at the barycenter may not be the most representative one. The shape of the triangle should be in some way taken into account in order to reflect the local feature characteristics more faithfully. The expected value of the local feature  $E\{S \mid T\}$  over the triangle  $T$  is more informative than the feature value only sampled at a single point, the barycenter of the triangle.

Consider  $T$  as an arbitrary triangle in 3D space with vertices  $A$ ,  $B$ , and  $C$  represented by  $\mathbf{p}_A$ ,  $\mathbf{p}_B$ , and  $\mathbf{p}_C$ , respectively, (see Figure 2). By noting  $\mathbf{e}_1 = \mathbf{p}_B - \mathbf{p}_A$  and  $\mathbf{e}_2 = \mathbf{p}_C - \mathbf{p}_A$ , we can obtain a parametric representation for a point  $P$  inside the triangle  $T$  as  $\mathbf{p} = \mathbf{p}_A + x\mathbf{e}_1 + y\mathbf{e}_2$ , where the two parameters  $x$  and  $y$  satisfy the constraints  $x, y \geq 0$  and  $x + y \leq 1$ . We assume that the point  $P$  is uniformly distributed inside the triangle  $T$ . Thus, the expected value of the  $i$ th component of  $S$ , denoted by  $E\{S_i \mid T\}$ , is given by

$$E\{S_i \mid T\} = \iint_{\Omega} S_i(x, y) f(x, y) dx dy, \quad i = 1, \dots, d, \quad (5)$$

where  $S_i(x, y)$  is the feature value at  $(x, y)$  and  $f(x, y)$  is the probability density function of the pair  $(x, y)$  over the domain  $\Omega = \{(x, y) : x, y \geq 0, x + y \leq 1\}$ . Accordingly,  $f(x, y) = 2$  when  $(x, y) \in \Omega$  or zero otherwise. The integration is performed over the domain  $\Omega$ . To approximate (5), we apply Simpson's 1/3 numerical integration formula [26]. We avoid the arbitrariness in vertex labeling by considering the three permutations of the labels  $A$ ,  $B$ , and  $C$ . This yields us three approximations, which are in turn averaged to

yield

$$\begin{aligned} E\{S_i \mid T\} \approx & \left(\frac{1}{27}\right) (S_i(\mathbf{p}_A) + S_i(\mathbf{p}_B) + S_i(\mathbf{p}_C)) \\ & + \left(\frac{4}{27}\right) \left( S_i\left(\frac{\mathbf{p}_A + \mathbf{p}_B}{2}\right) + S_i\left(\frac{\mathbf{p}_A + \mathbf{p}_C}{2}\right) \right. \\ & \left. + S_i\left(\frac{\mathbf{p}_B + \mathbf{p}_C}{2}\right) \right) \\ & + \left(\frac{4}{27}\right) \left( S_i\left(\frac{2\mathbf{p}_A + \mathbf{p}_B + \mathbf{p}_C}{4}\right) \right. \\ & \left. + S_i\left(\frac{\mathbf{p}_A + 2\mathbf{p}_B + \mathbf{p}_C}{4}\right) \right. \\ & \left. + S_i\left(\frac{\mathbf{p}_A + \mathbf{p}_B + 2\mathbf{p}_C}{4}\right) \right). \end{aligned} \quad (6)$$

Equation (6) boils down to take a weighted average of feature values calculated at 9 points on the triangle.

### 3.4. Bandwidth selection

There are three levels of analysis at which the parameters in the bandwidth matrix  $H_k$  involved in KDE can be chosen (see (4) in Section 3.2).

(1) *Triangle level*: this option allows a distinct bandwidth parameter for each triangle in the mesh. In principle, this choice is very flexible since it does not make any assumptions about the shape of the kernel function and hence about the shape of the  $k$ th triangle. In general, finding a KDE bandwidth matrix specific to each observation is a difficult problem [25]. For the Gaussian kernel, however, estimation of the bandwidth matrix  $H_k$  reduces to the estimation of the feature covariance matrix. The moment formula in (5) and its numerical approximation in (6) can directly be used for moments of any order. For example, the  $(i, j)$ th component  $h_{ij}$  of  $H$  is computed by

$$\begin{aligned} h_{ij} = & \iint_{\Omega} S_i(x, y) S_j(x, y) f(x, y) dx dy \\ & - \iint_{\Omega} S_i(x, y) f(x, y) dx dy \\ & \times \iint_{\Omega} S_j(x, y) f(x, y) dx dy, \quad i, j = 1, \dots, d. \end{aligned} \quad (7)$$

(2) *Mesh level*: the second option is to use a fixed bandwidth matrix for all triangles in a given mesh, but different bandwidths for different meshes. In this case, the bandwidth matrix for a given feature can be obtained from its observations using Scott's rule of thumb [14]:  $H_{\text{Scott}} = (\sum_k w_k^2)^{1/(d+4)} \hat{C}^{1/2}$ , where  $d$  is the dimension of the feature,  $\hat{C}$  is the estimate of the feature covariance matrix, and  $w_k$  is the weight associated to each observation. Scott's rule of thumb is proven to provide the optimal bandwidth in terms of estimation error when the kernel function and the unknown density are both Gaussian. Although, there is no guarantee that feature distributions to be Gaussian, Scott's rule of thumb is still used for its simplicity.

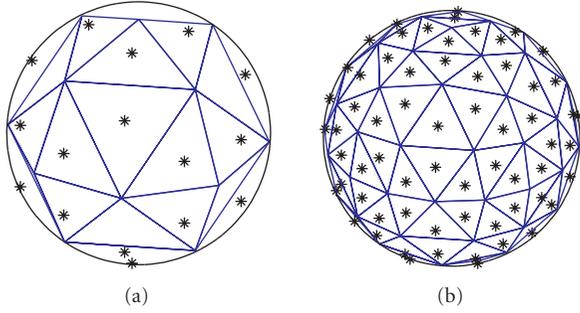


FIGURE 3: Distribution of target points over the unit-sphere, obtained by subdividing an octahedron once (left: 32 points) and twice (right: 128 points).

(3) *Database level*: in the last option, the bandwidth parameter is fixed for all triangles and meshes, that is,  $H_k = H$ . Setting the bandwidth at database level has the implicit effect of smoothing the resulting densities. In this case, we estimate the bandwidth parameters from a representative subset of the database by averaging the Scott bandwidth matrices over the selected meshes.

### 3.5. Choice of the targets

Targets are defined as the points at which the feature density functions are explicitly calculated. The density values computed at these targets constitute the 3D shape feature vector. Selection of target points must result in parsimonious yet discriminative descriptors. For single-dimensional features, it suffices to uniformly sample the density function within its dynamic range. However, the multidimensional features,  $S_r$ ,  $S_t$ , and  $S_c$ , which consist of magnitude and direction components, require more attention. We denote the target size by  $N_{\text{mag}}$  for the magnitude component and by  $N_{\text{dir}}$  for the direction component. The target points for these multidimensional features are then obtained by the Cartesian product of the two sets, yielding an overall target set size of  $N = N_{\text{mag}} \times N_{\text{dir}}$ . The magnitude components of  $S_r$  and  $S_t$  are uniformly quantized in the interval  $[0, r_{\text{max}}]$ , while those of  $S_t$  in the  $[0, d_{t,\text{max}}]$  interval. The setting of  $r_{\text{max}}$  and  $d_{t,\text{max}}$  is discussed in Section 4.2. The direction components of  $S_r$  and  $S_t$  features, namely,  $\hat{\mathbf{r}}_p$  and  $\hat{\mathbf{n}}_p$ , lie on the unit sphere. To complete the design of target points, following [12], we consider an octahedron circumscribed by the unit sphere and we subdivide each of its 8 triangles into four, twice, by radially projecting back the subdivided triangles to the surface of the sphere. As targets of the direction components of  $S_r$  and  $S_t$ , we select the barycenters of the resulting 128 triangles, 16 per each of the 8 faces of the octahedron. This leads to a uniform partitioning of the sphere, as shown in Figure 3.

The  $S_c$  feature has a direction component  $\mathbf{c}_p$  with non-unit norm, which lies within the unit ball. For the target set of the direction component  $\mathbf{c}_p$ , we thus similarly consider octahedra, but circumscribed by spheres of various radii. We take four such octahedra within spheres of radial length 0.25, 0.5, 0.75, and 1. We subdivide the two inner octahedra once, each

yielding 32 targets, and the two outer octahedra twice, each yielding 128 targets. This gives a total of  $N_{\text{dir}} = 320$  regularly spaced targets for the  $\mathbf{c}_p$ -component of the  $S_c$  feature. The inner spheres have sparser targets to balance out the target densities of the outer spheres.

### 3.6. Computational complexity of KDE

The computational complexity of KDE using directly (4) is  $O(KN)$ , where  $K$  is the number of observations (the number of triangles in our case) and  $N$  is the number of density evaluation points, that is, targets. For applications such as content-based retrieval, the  $O(KN)$ -complexity is prohibitive. To give an example, on a Pentium 4 PC (2.4 GHz CPU, 2 GB RAM) and for a mesh of 130,000 triangles, the direct evaluation of the  $S_r$ -descriptor (1024-point pdf) takes 125 seconds. However, when the kernel function in (4) is chosen as Gaussian, we can use the fast Gauss transform (FGT) [15, 16] to reduce the computational complexity by two orders of magnitude. For example, with FGT, the  $S_r$ -descriptor computation takes only 2.5 seconds. FGT is an approximation scheme enabling the calculation of large sums of Gaussians within reasonable accuracy and reducing the complexity down to  $O(K + N)$ . In our 3D shape description system, we have used an improved version of FGT implemented by Yang et al. [16].

For the sake of completeness, we provide the conceptual guidelines of the FGT algorithm (see [15, 16] for mathematical and implementation details). FGT is a special case of the more general fast multipole method [15], which trades off computational simplicity for acceptable loss of accuracy. The basic idea is to cluster the data points and target points using appropriate data structures and to replace the large sums with smaller ones that are equivalent up to a given precision. In the case of FGT, each exponential in the sum is shifted and expanded into a truncated Hermite series in  $O(K)$  operations. The gain in complexity is achieved by avoiding the computation of every Gaussian at every evaluation point unlike the direct approach, which has  $O(KN)$ -complexity. The accuracy can be controlled by the truncation order. Truncated Hermite series are constructed about a small number of cluster centers formed by target points; the series are shifted to target cluster centers, and then evaluated at  $N$  targets in  $O(N)$  operations. Since the two sets of operations are disjoint, the total complexity of FGT becomes  $O(K + N)$ .

### 3.7. Flow diagram of the algorithm

We summarize below the proposed algorithm to obtain a density-based 3D shape descriptor.

- (1) For a chosen local feature  $S$ , specify a set of targets  $t_n$ ,  $n = 1, \dots, N$ .
- (2) Normalize the 3D triangular mesh  $\mathcal{M} = \bigcup_{k=1}^K T_k$  according to the invariance requirements of  $S$ .
- (3) For each mesh triangle  $T_k$ , calculate its feature value  $s_k$  using (6) and its weight  $w_k$ .

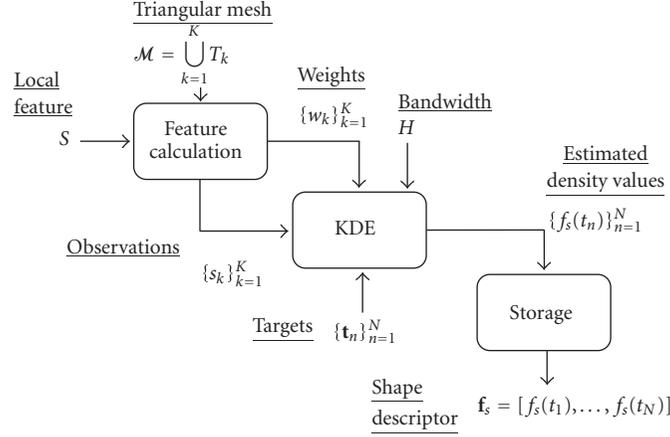


FIGURE 4: Flow diagram to compute a density-based 3D shape descriptor when the bandwidth is set at database level.

- (4) Set the bandwidth parameters  $H_k$  according to the strategy chosen among the three options described in Section 3.4.
- (5) For each target  $t_n$ ,  $n = 1, \dots, N$ , evaluate the local feature density  $f_s(t_n)$ , using (4).
- (6) Store the resulting density values  $f_s(t_n)$  in the shape descriptor  $\mathbf{f}_s = [f_s(t_1), \dots, f_s(t_N)]$ .

Note that the descriptors corresponding to  $L$  different local features  $S_1, \dots, S_L$  can be concatenated to obtain a combined descriptor  $\mathbf{f}_{S_1, \dots, S_L} = [\mathbf{f}_{S_1}, \dots, \mathbf{f}_{S_L}]$ . Figure 4 depicts the flow diagram of the algorithm when the bandwidth parameters are set at database level. Alternatively, in the triangle or mesh level setting, a bandwidth matrix is to be computed for each triangle or for the entire mesh, respectively. Note that in Figure 4, we assume that the mesh  $\mathcal{M}$  has already undergone a pose and/or scale normalization step depending on the missing invariance properties of the local feature  $S$  chosen.

#### 4. EXPERIMENTAL RESULTS

In this section, we illustrate the performance of the proposed shape descriptors in 3D retrieval applications. When a query model is presented to the 3D object database, its descriptor is calculated and then compared to all the stored descriptors using a distance function. The outcome is a set of database models sorted in increasing distance. The models at the top of the list are expected to resemble the queried model more than those at the bottom of the list.

We have experimented on two different 3D model databases: the Princeton Shape Benchmark (PSB) [5] and the Sculpteur Database (SCUdb) [6, 27]. Both databases consist of objects described as triangular meshes, though they differ substantially in terms of content and mesh quality. PSB is a publicly available database containing a total of 1814 synthesis models, categorized into general classes such as animals, humans, plants, household objects, tools, vehicles, buildings, and so forth. An important feature of the database is the availability of two equally sized sets. One of them is a training

set (90 classes) reserved for tuning the parameters involved in the computation of a particular shape descriptor, and the other for testing purposes (92 classes). By contrast, SCUdb is a private database containing over 800 models corresponding mostly to scanned archeological objects residing in museums [6, 27]. Presently, 513 of the models are classified into 53 categories with comparable set populations, which include utensils of ancient times (e.g., amphorae, vases, bottles, etc.), pavements, and artistic objects such as human statues (parts or as a whole), figurines, and moulds. The database has been augmented by artificially generated 3D objects such as spheres, tori, cubes, or cones in order to build a set of simple well-controlled classes. The meshes in SCUdb are highly detailed and reliable in terms of connectivity and orientation of triangles. To give an idea of the significant differences between PSB and SCUdb, we can quote average mesh resolution figures. The average number of triangles in SCUdb and in PSB is 175250 and 7460, respectively, corresponding to a ratio of 23. In terms of vertices, SCUdb meshes contain 87670 vertices on the average while for PSB this number is 4220. Furthermore, the average triangular area relative to the total mesh area is 33 times smaller in SCUdb than in PSB.

##### 4.1. Evaluation tools

The most commonly used statistics for measuring the performance of a shape descriptor in a content-based retrieval application are summarized below [5].

###### (i) Precision-recall curve

For a query  $q$  that is a member of a certain class, *Precision* (vertical axis) is the ratio of the relevant matches  $K_q$  (matches that are within the same class as the query) to the number of retrieved models  $K_{\text{ret}}$ , and *Recall* (horizontal axis) is the ratio of relevant matches  $K_q$  to the size of the query class  $C_q$ :

$$\text{Precision} = \frac{K_q}{K_{\text{ret}}}, \quad \text{Recall} = \frac{K_q}{C_q}. \quad (8)$$

(ii) *Nearest neighbor (NN)*

The percentage of the first-closest matches that belong to the query class.

(iii) *First-tier and second-tier*

First-tier (FT) is the recall when the number of retrieved models is the same as the size of the query class and second-tier (ST) is the recall when the number of retrieved models is two times the size of the query class.

(iv) *E-measure*

This is a composite measure of the precision and recall for a fixed number of retrieved models, for example, 32, based on the intuition that a user of a search engine is more interested in the first page of query results than in later pages. E-measure is given by

$$E = \frac{2}{1/\text{precision} + 1/\text{recall}}. \quad (9)$$

(v) *Discounted cumulative gain*

A statistic that weights correct results near the front of the list more than correct results later in the ranked list under the assumption that a user is less likely to consider elements near the end of the list. Specifically, the ranked list of retrieved objects is converted to a list  $L$ , where an element  $L_k$  has value 1 if the  $k$ th object in the ranked list is in the same class as the query and otherwise has value 0. Discounted cumulative gain  $DCG_k$  is then defined as

$$DCG_k = \begin{cases} L_k, & k = 1, \\ DCG_{k-1} + \frac{L_k}{\log_2(k)}, & \text{otherwise.} \end{cases} \quad (10)$$

The final DCG score for a query  $q$  is obtained for  $k = K_{\max}$ , where  $K_{\max}$  is the total number of objects in the database, and normalizing  $DCG_{K_{\max}}$  by the maximum possible DCG that would be achieved if the first  $C_q$  retrieved elements were in the class of the query  $q$  ( $C_q$  is the size of the query class). Thus DCG reads as

$$DCG = \frac{DCG_{K_{\max}}}{1 + \sum_{k=2}^{C_q} (1/\log_2(k))}. \quad (11)$$

(vi) *Normalized DCG*

This is a very useful statistic based on averaging DCG values of a set of algorithms on a particular database. Normalized DCG (NDCG) gives the relative performance of an algorithm with respect to the other ones. A negative value means that the performance of the algorithm is below the average; similarly a positive value indicates above the average performance. Let  $DCG^{(A)}$  be the DCG of a certain algorithm  $A$  and let  $DCG^{(\text{avg})}$  be the average DCG values of a series of algorithms on the same database, then NDCG for the algorithm

TABLE 3: Histogram-based 3D shape descriptors and their sizes.

Descriptor	Acronym	Size $N$
<i>Cord and angle histograms</i> [11]	CAH	$4 \times 64 = 256$
<i>D1-distribution</i> [10]	D1	64
<i>D2-distribution</i> [10]	D2	64
<i>EGI</i> [8]	EGI	128
<i>3DHT</i> [12]	3DHT	$8 \times 128 = 1024$

$A$  is defined as

$$NDCG^{(A)} = \frac{DCG^{(A)}}{DCG^{(\text{avg})}} - 1. \quad (12)$$

All these quantities are normalized within the range  $[0, 1]$  (except NDCG) and higher values reflect better performance. In order to give the overall performance of a shape descriptor on a database, the values of a statistic for each query are averaged to yield a single performance figure. The retrieval statistics presented in the sequel are obtained using the utility software included in PSB [5].

## 4.2. Retrieval experiments

In all of our retrieval experiments, we use the Minkowski- $l_1$  distance measure to assess the similarity between descriptors since we have observed that this distance function gives better performance in most of the cases as compared to other distance measures such as  $l_2$  or  $\chi^2$ . We apply the following normalization to all the meshes of the database to secure RST invariance of the features. For translation invariance, the object's center of mass is translated to the origin. For scale invariance, the area-weighted average distance of surface points to the origin is set to unity. We have observed that, with this scaling operation, the frequency of the distance of a surface point to the mesh center exceeding 2 becomes negligible. This allows us to set empirical upper limits  $r_{\max}$  and  $d_{t,\max}$  to the magnitude components  $r_P$  and  $d_{t,P}$ , respectively. Finally, to guarantee rotation and reflection invariance, we follow the "continuous" PCA approach of Vranić [7]. All the codes for our descriptors as well as for those proposed in the literature (cord and angle histograms [11], D1 and D2 shape distributions [10], EGI [8] and CEGI [9], 3DHT [12]) have been implemented in MATLAB 7.0 (R14) environment, using C MEX external interface for time-consuming jobs. For FGT, we have used the implementation provided by Yang et al. [16].

The acronyms of the descriptors we have experimented are listed in Tables 3 and 4. They will subsequently be used in graph annotations. The details about descriptor sizes are given in the corresponding sections.

There are two alternative ways of combining descriptors, by multivariate density evaluation or by concatenating estimated univariate densities. The multivariate descriptors ( $S_r$ ,  $S_t$ ,  $S_c$ , and  $S_n$ ) that we consider in our experiments are derived from  $S_r$ ,  $S_t$ ,  $S_c$ , and  $S_n$  features as given in the first four rows of Table 4. Alternatively, descriptors for multiple scalar features, for example,  $S_{r_i}$ ,  $i = 1, \dots, 4$ , can

TABLE 4: Density-based 3D shape descriptors and their sizes.

Descriptor	Acronym	Size $N$
Radial ( $S_r$ ) density	Sr	$8 \times 128 = 1024$
Tangent pl. ( $S_t$ ) density	St	$8 \times 128 = 1024$
Cross-product ( $S_c$ ) density	Sc	$8 \times 320 = 2560$
Normal ( $S_n$ ) density	Sn	128
Univ. dens. of $S_r$ components	[Sr1,Sr2,Sr3,Sr4]	$4 \times 64 = 256$
Univ. dens. of $S_t$ components	[St1,St2,St3,St4]	$4 \times 64 = 256$

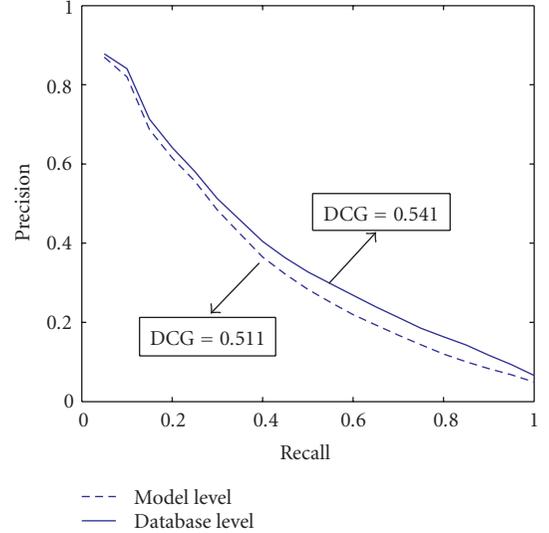
TABLE 5: DCG values for possible bandwidth selection strategies on PSB training meshes.

Bandwidth setting	Sr	St	Sc
Triangle level	0.352	—	—
Mesh level	0.511	0.514	0.499
Database level	0.541	0.567	0.543

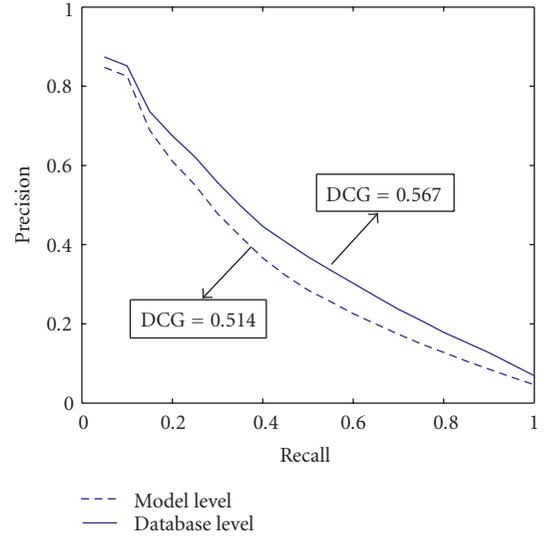
separately be computed by univariate density estimation and then concatenated in a joint vector, as in the last two rows of Table 4. Let  $A_1, A_2, \dots, A_L$  denote  $L$  generic (one- or multidimensional) features and let  $\mathbf{f}_{A_1}, \mathbf{f}_{A_2}, \dots, \mathbf{f}_{A_L}$  denote the corresponding density-based descriptors with  $N_1, N_2, \dots, N_L$  components, respectively, ( $N_i$ ,  $i = 1, \dots, L$  corresponds to the number of target points on which the density of feature  $A_i$  has been evaluated or equivalently to the size of the vector  $\mathbf{f}_{A_i}$ ). Square bracketing  $[A_1, A_2, \dots, A_L]$  that appears in subsequent graphs and tables indicates the concatenation of the shape descriptors  $[\mathbf{f}_{A_1}, \mathbf{f}_{A_2}, \dots, \mathbf{f}_{A_L}]$  resulting in a vector of size  $N_1 + N_2 + \dots + N_L$ . For notational simplicity, we will refer to the descriptor  $\mathbf{f}_{A_1}$  consisting of the density vector as A1-descriptor; similarly,  $[A1, A2]$  will be the shorthand notation for the descriptor  $[\mathbf{f}_{A_1}, \mathbf{f}_{A_2}]$ . Note finally that the generic feature  $A_i$  can be either a vector by construction or a scalar obtained by taking a component of some other multidimensional feature.

#### 4.2.1. Impact of bandwidth selection

The KDE approach critically depends upon the judicious setting of the bandwidth parameters. We tested the triangle, mesh and database level alternatives presented in Section 3.4 on our multidimensional local features  $S_r$ ,  $S_t$ , and  $S_c$  (the computationally expensive triangle-level setting was only tested for  $S_r$ ). Since we have observed that the off-diagonal terms of the bandwidth matrices are negligible as compared to the diagonal terms, we use only diagonal bandwidth matrices  $H = \text{diag}(h_1, \dots, h_d)$ . For the mesh level and database level, we apply the Scott's rule-of-thumb. For the triangle level, we employ the KDE toolbox developed by Ihler [28] since the available FGT implementation does not allow a different bandwidth per triangle [16]. The KDE toolbox makes use of kd-trees and reduces the computational burden considerably, though not to the extent achieved by FGT. Table 5 compares the DCG scores obtained with Sr, St, and Sc-descriptors on the PSB training set. Figure 5 shows the precision-recall plots corresponding to mesh and database



(a)



(b)

FIGURE 5: Precision-recall curves with a bandwidth selection made at mesh level versus database level for Sr-descriptor (a) and St-descriptor (b) on PSB training mesh.

level settings for Sr and St-descriptors. We clearly observe that setting the bandwidth  $H$  at database level is more advantageous as compared to triangle and mesh level settings. Any further results reported are therefore for the database level setting of  $H$ . In Table 6, we provide the average Scott bandwidth values obtained from PSB training meshes for  $S_r$ ,  $S_t$ , and  $S_c$  features.

#### 4.2.2. Univariate versus multivariate density-based descriptors

In this section, we compare the impact of combining descriptors on the retrieval performance. As discussed before,

TABLE 6: The average Scott bandwidth obtained from the PSB training meshes.

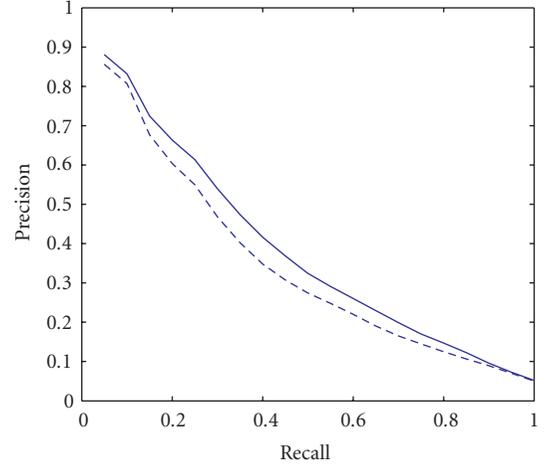
Descriptor	$h_1$	$h_2$	$h_3$	$h_4$
Sr	0.20	0.35	0.25	0.15
St	0.20	0.25	0.25	0.30
Sc	0.20	0.15	0.25	0.25

descriptors can be compounded either by concatenating univariate descriptors or by multivariate density estimation. One can conjecture that the multivariate descriptors, resulting from the joint density functions of features, are richer in information content since component-wise dependencies are also taken into account. On the other hand, univariate densities are much simpler to estimate and do not incur into dimensionality problems. In our experiments, each univariate density is evaluated at 64 target points. Accordingly, a 4-tuple concatenation, such as  $[Sr1, Sr2, Sr3, Sr4]$ , results in a descriptor of size  $N = 4 \times 64 = 256$ . For multivariate density descriptors Sr and St, recall that  $N_{dir} = 128$  and for Sc,  $N_{dir} = 320$  (see Section 3.5).  $N_{mag}$  being chosen equal to 8 in all cases, the size of the Sr and St-descriptors is  $N = 8 \times 128 = 1024$  and the size of the Sc-descriptor is  $N = 8 \times 320 = 2560$ . Figures 6 and 7 with Table 7 explicitly show that the multivariate density-based descriptors are superior to the descriptors obtained by the concatenation of univariate densities for all feature types on both databases.

#### 4.2.3. Comparison of density-based descriptors with their histogram-based peers

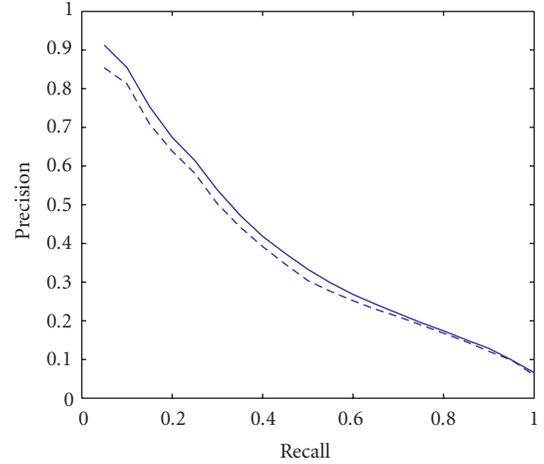
One of the motivations of this work is to show that a considerable improvement in the retrieval performance can be obtained by more rigorous and accurate computation of shape distributions as compared to more practical ad hoc histogram approaches. Notice that we interpret the term “histogram-based descriptor” for any count-and-accumulate type of procedure. This way we can refer to analogous descriptors in the literature as histogram-based whenever they count-and-accumulate local information to obtain a global shape descriptor [8–12].

An interesting case in point is Cord and Angle Histograms (CAH) [11]. The features in CAH are identical to the individual scalar components  $r_P, \hat{r}_{P,x}, \hat{r}_{P,y}$ , and  $\hat{r}_{P,z}$  of our  $S_r$  feature up to a parameterization. In [11], the authors consider the length of a cord (corresponding to  $r_P$ ) and the two angles between a cord and the first two principal directions (corresponding to  $\hat{r}_{P,x}$  and  $\hat{r}_{P,y}$ ). Notice that in our parameterization of  $S_r$ , we consider the Cartesian coordinates rather than the angles. In order to compare with our  $[Sr1, Sr2, Sr3, Sr4]$ -descriptor, we implemented the CAH-descriptor by also considering the histogram of the angle with the third principal direction. The resulting CAH-descriptor is thus the concatenation of one cord length and three angle histograms. Each histogram consisting of 64 bins leads to a descriptor of total size  $N = 4 \times 64 = 256$ .  $[Sr1, Sr2, Sr3, Sr4]$ -descriptor, again of size 256,



---  $[Sr1, Sr2, Sr3, Sr4]$   
— Sr

(a)



---  $[St1, St2, St3, St4]$   
— St

(b)

FIGURE 6: Precision-recall curves for  $[Sr1, Sr2, Sr3, Sr4]$  versus Sr (a) and  $[St1, St2, St3, St4]$  versus St (b) on PSB.

differs from CAH in three aspects: first, it uses a different parameterization of the angle (direction) components; second, the local feature values are calculated by (6) instead of using mere barycentric sampling; third, it employs KDE instead of histogram computation. In Figure 8, we provide the precision-recall curve corresponding to CAH and  $[Sr1, Sr2, Sr3, Sr4]$  on PSB test set and on SCUdb. The respective DCG values are 0.434 and 0.501 for PSB, 0.681 and 0.698 for SCUdb, indicating the superior performance of our framework under identical feature sets. An additional improvement can be gained by estimating the joint density of  $S_r$ , leading to the Sr-descriptor. That is, in contrast to the concatenation of univariate densities, we directly use the joint density of  $S_r$  as a descriptor. The DCG value

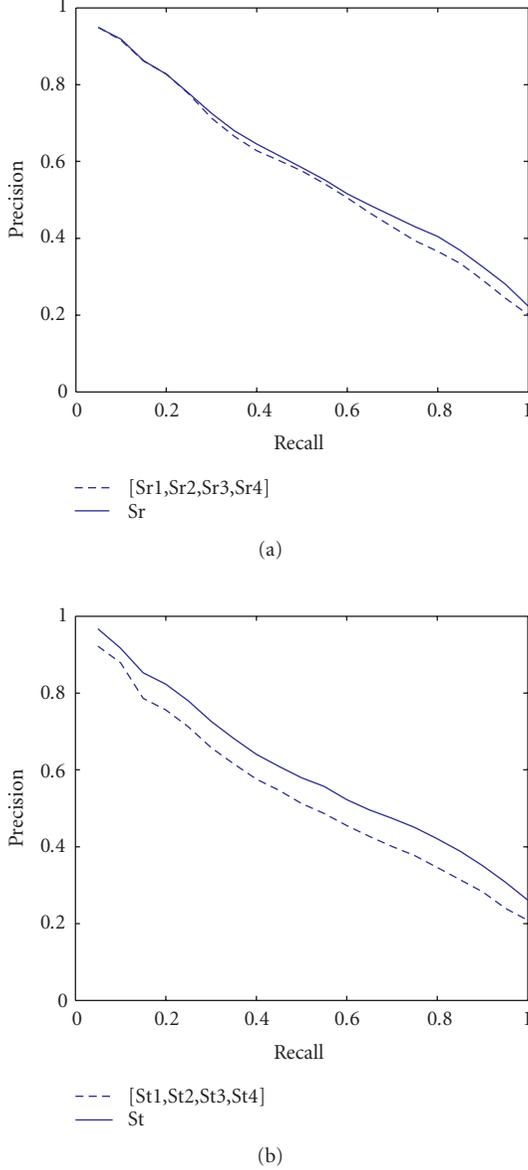


FIGURE 7: Precision-recall curves for [Sr1,Sr2,Sr3,Sr4] versus Sr (a) and [St1,St2,St3,St4] versus St on SCUdb (b).

of the Sr-descriptor is 0.533 on PSB and 0.708 on SCUdb, one more step of improvement as compared to the concatenated univariate case [Sr1,Sr2,Sr3,Sr4] (DCG = 0.501 on PSB and DCG = 0.698 on SCUdb). Note that the performance improvement using our scheme is less impressive over SCUdb than over PSB. This can be explained by the fact that SCUdb meshes are much denser than PSB meshes in number of triangles. As the number of observations increases, the accuracies of the histogram method and KDE become comparable and both methods result in similar descriptors. This also indicates that the KDE methodology is especially appropriate for coarser mesh resolutions as in PSB.

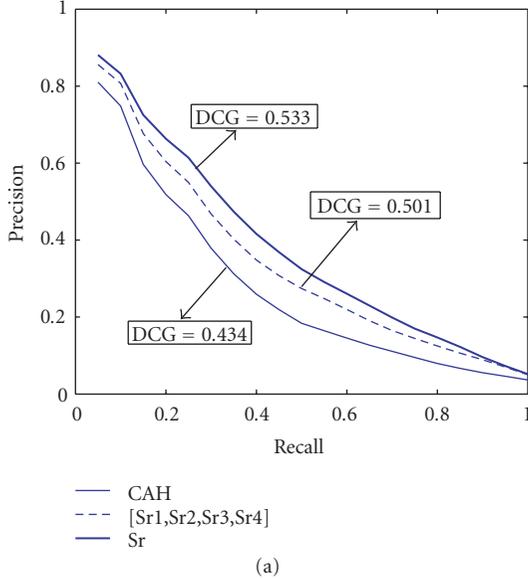
A second instance of our framework outperforming its competitor is with the EGI-descriptor [2, 5, 8], which

TABLE 7: Retrieval statistics for univariate and multivariate density-based descriptors.

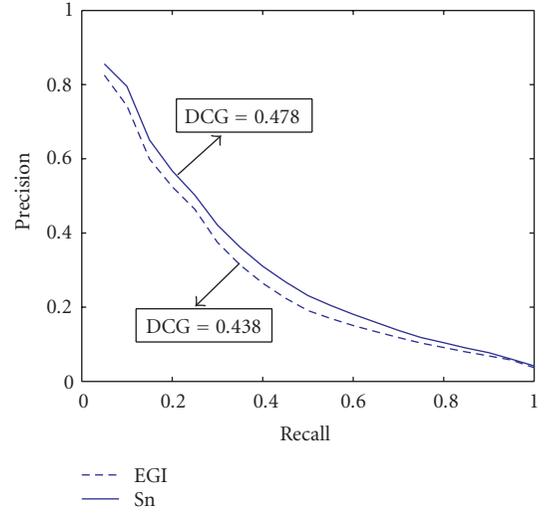
	Descriptor	NN	FT	ST	E	DCG
PSB	[Sr1,Sr2,Sr3,Sr4]	0.436	0.222	0.306	0.180	0.501
	Sr	0.499	0.260	0.343	0.201	0.533
	[St1,St2,St3,St4]	0.451	0.250	0.348	0.202	0.533
	St	0.523	0.267	0.364	0.210	0.543
SCUdb	[Sr1,Sr2,Sr3,Sr4]	0.701	0.430	0.555	0.314	0.698
	Sr	0.745	0.452	0.568	0.323	0.709
	[St1,St2,St3,St4]	0.632	0.400	0.520	0.298	0.662
	St	0.754	0.473	0.575	0.324	0.712

consists of binning the surface normals. The density of our  $S_n(P) = \hat{\mathbf{n}}_P$  feature is equivalent to the EGI-descriptor. There can be different choices for binning surface normals, for example, by mapping the normal of a certain mesh triangle to the closest bin over the unit sphere and augmenting that bin by the relative area of the triangle. Such an approach requires a very densely discretized unit sphere and the resulting descriptor is not very efficient in terms of storage. In the present work, similarly to [12], we preferred the following implementation for the EGI-descriptor. First, 128 unit norm vectors  $\hat{\mathbf{n}}_{\text{bin},j}$ ,  $j = 1, \dots, 128$ , are obtained as histogram bin centers by octahedron subdivision, as described in Section 3.5. Then, the contribution of each triangle  $T_k$ ,  $k = 1, \dots, K$ , with normal vector  $\hat{\mathbf{n}}_k$  to the  $n$ th bin center is computed as  $w_k |\langle \hat{\mathbf{n}}_k, \hat{\mathbf{n}}_{\text{bin},j} \rangle|$  if  $|\langle \hat{\mathbf{n}}_k, \hat{\mathbf{n}}_{\text{bin},j} \rangle| \geq 0.7$  or otherwise as zero (recall that  $w_k$  is the relative area of the  $k$ th triangle). The use of the absolute value is needed because some models as those in the PSB set cannot provide orientation information. The Sn-descriptor of the same size, that is, 128, achieves a superior DCG of 0.478 as compared to the DCG score of 0.438 for EGI on PSB (see Figure 9). For SCUdb, the DCG-performance differential is even more pronounced (DCG = 0.589 for Sn, DCG = 0.535 for EGI) noting that for low recall values (recall < 0.2), the EGI-descriptor is better than Sn (see Figure 9).

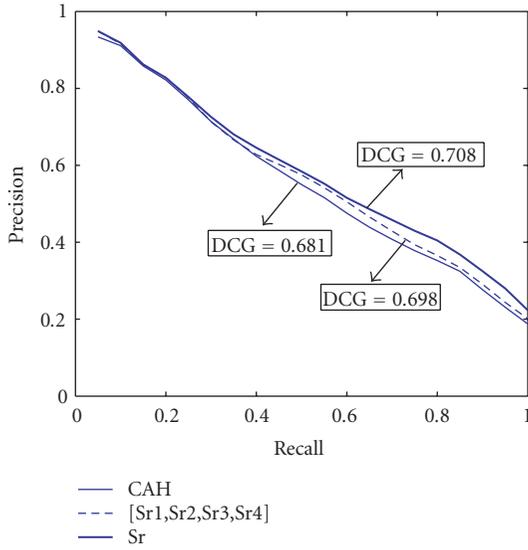
A third instance of comparison can be considered between our St-descriptor and the 3DHT-descriptor [12] since both of them use local tangent plane parameterization. The procedure for the 3DHT descriptor is carried out as follows. We first recall that the 3DHT-descriptor is a histogram constructed by accumulating mesh surface points over planes in 3D space. Each histogram bin corresponds to a plane  $\mathcal{P}_{ij}$  parameterized by its normal distance  $d_{i,i}$ ,  $i = 1, \dots, N_{\text{mag}}$ , to the origin and its normal direction  $\hat{\mathbf{n}}_{\text{bin},j}$ ,  $j = 1, \dots, N_{\text{dir}}$ . Clearly, there can be  $N_{\text{mag}} \times N_{\text{dir}}$  such planes and the resulting descriptor is of size  $N = N_{\text{mag}} \times N_{\text{dir}}$ . We can obtain such a family of planes exactly as described in Section 3.5 and in [12]. In our experiments, we have used  $N_{\text{mag}} = 8$  distance bins sampled within the range  $[0, 2]$  and  $N_{\text{dir}} = 128$  uniformly sampled normal directions. This results in a 3DHT descriptor of size  $N = 1024$ . To construct the Hough array, one first takes a plane with normal direction  $\hat{\mathbf{n}}_{\text{bin},j}$ ,  $j = 1, \dots, N_{\text{dir}}$ , at each triangle barycenter  $\mathbf{m}_k$ ,  $k = 1, \dots, K$ ,



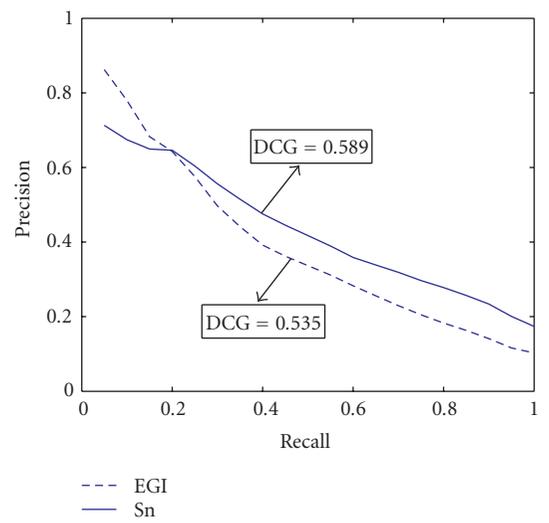
(a)



(a)



(b)



(b)

FIGURE 8: Precision-recall curves for CAH, [Sr1,Sr2,Sr3,Sr4] (concatenated) and Sr (joint) on PSB test set (a) and SCUdb (b).

FIGURE 9: Precision-recall curves for EGI and Sn on PSB test set (a) and SCUdb (b).

and then calculates the normal distance of the plane to the origin by  $|\langle \mathbf{m}_k, \hat{\mathbf{n}}_{\text{bin},j} \rangle|$ . The resulting value is quantized to the closest  $d_{t,i}$ ,  $i = 1, \dots, N_{\text{mag}}$ , and then the bin corresponding to the plane  $\mathcal{P}_{ij}$  is augmented by  $w_k |\langle \hat{\mathbf{n}}_k, \hat{\mathbf{n}}_{\text{bin},j} \rangle|$  if  $|\langle \hat{\mathbf{n}}_k, \hat{\mathbf{n}}_{\text{bin},j} \rangle| \geq 0.7$  (the value of 0.7 is suggested by Zaharia and Prêteux [12]) and we have also verified its performance-wise optimality). In Figure 10, we compare the St- and the 3DHT-descriptors in terms of precision-recall curves. On PSB, the St-descriptor yields a DCG of 0.543, a worse score against 0.577 of the 3DHT-descriptor. This can be attributed largely to the fact that the 3DHT-descriptor employs an implicit correction for normal orientations by the weighting scheme  $w_k |\langle \hat{\mathbf{n}}_k, \hat{\mathbf{n}}_{\text{bin},j} \rangle|$  according to which only normal direction  $\hat{\mathbf{n}}_k$  matters but not its orientation. Our St-descriptor

does not make use of such a correction and considers the normal orientations as they are provided by the list of triangles in the mesh. Accordingly, we explain the negative performance gap between St and 3DHT by the fact that, on PSB meshes, information regarding normal orientations might be compromised. On the other hand, for SCUdb, the performance of St (DCG = 0.712) parallels that of 3DHT noting that 3DHT remains slightly better (DCG = 0.727).

#### 4.2.4. General performance comparison

In this section, we compare the descriptors that we propose (univariate, concatenated, or multivariate) first among

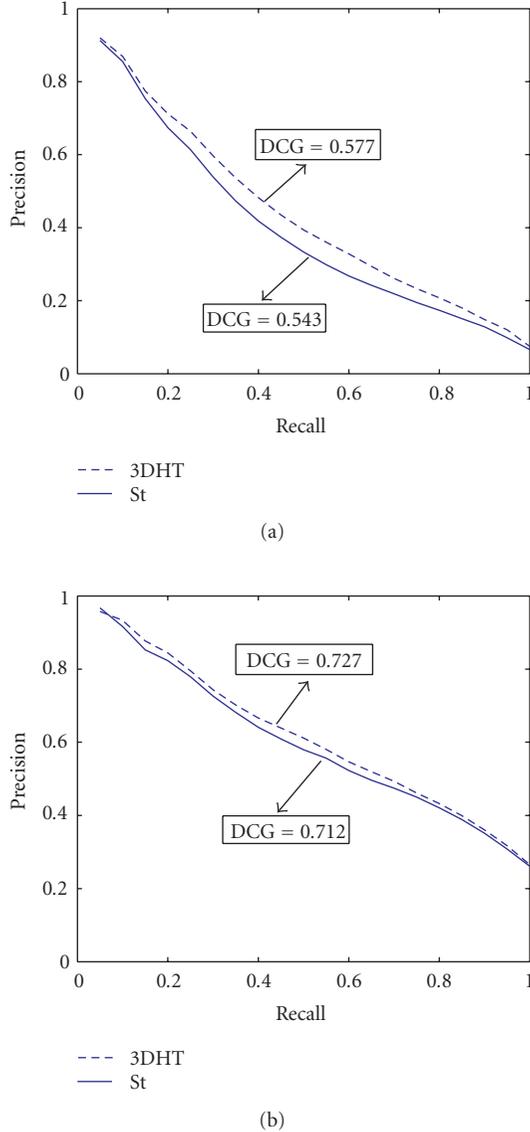


FIGURE 10: Precision-recall curves for 3DHT and St on PSB test set (a) and SCUdb (b).

themselves and then with various other descriptors existing in the literature.

In Table 8, we see the competition within the Sr, St, and Sc set and their various combinations. Since pairing the features results in higher dimensions (8 or 12) precluding multivariate density estimation, we use concatenation of the 4-variate densities. It is interesting to observe that the pairwise concatenations [Sr,St], [Sr,Sc], and [St,Sc] of size 2048, 3584 and 3584, respectively, increase the DCG and NN scores significantly. We can conclude that each local feature must be reporting aspects on the shape not covered by the remaining ones, albeit their similarity. Furthermore, the triplet concatenation [Sr,St,Sc] of size 4608 boosts the DCG and NN performance further. We also note that, on a Pentium 4 PC (2.4 GHz CPU, 2 GB RAM), the [Sr,St,Sc]-descriptor can be computed in less than one second on the average over

PSB test set meshes, which indicates that our density-based descriptors are very time-efficient and suitable for practical online applications.

Table 9 finally summarizes the experimental results conducted to compare our density-based descriptors with other histogram-based descriptors. For both databases, PSB and SCUdb, the [Sr,St,Sc]-descriptor comes at the top in all performance fields. Furthermore, the second place is taken by a pairwise concatenation which is more storage-efficient and even more time-efficient than [Sr,St,Sc]: [Sr,St] for PSB and [St,Sc] for SCU.

The density-based framework does not only outperform histogram-based descriptors but also proves to be effective as compared to other more general state-of-the-art shape descriptors. In fact, based on the scores on PSB test set reported in [5], the [Sr,St,Sc]-descriptor has the highest DCG score among all other well-known 3D shape descriptors, as shown in Figure 11. Except for 3DHT [12] and CAH [11], all the descriptor scores shown in Figure 11 are taken from [5]. We refer the reader to [5] for brief descriptions and acronyms of these descriptors. The [Sr,St,Sc]-descriptor has a DCG value of 0.607, while the next best descriptor radialized extent function (REXT) [7, 24] has a DCG value of 0.601 [5]. Note also that the [Sr,St]-descriptor (DCG = 0.599) ranks third in the competition. The average REXT-descriptor size reported in [5] is 17.5 kilobytes, while for our [Sr,St,Sc]-descriptor this figure is 22 kilobytes. The average generation time for the REXT-descriptor is 2.2 seconds [5], while our [Sr,St,Sc]-descriptor can be computed in 0.9 seconds on the average on comparable hardware configurations.

## 5. CONCLUSION

We have proposed a novel methodology to obtain 3D shape descriptors and evaluated its impact in a retrieval scenario. We have shown that shape descriptors derived as kernel density estimates of local surface features prove more advantageous compared to the count-and-accumulate-based histogram descriptors. Firstly, one main advantage accrues from the fact that our descriptors are true probability density functions of geometrical quantities defined over the model surface. Secondly, our surface sampling is not as crude as just considering triangle barycenters or as profuse as random sampling, but judiciously chooses the triangle characteristics. Thirdly and most importantly, the KDE-based approach deals with multidimensional surface features as easily as with scalar features. The bandwidth parameters in KDE provide a more gracious control over finite sample-size and dimensionality problems, while with multivariate histograms one can only adjust the bin widths [13, 14]. The local surface information brought by multidimensional features proves to be more discriminating than scalar ones.

The proposed framework applies to 3D objects represented as triangular meshes but extension to point-cloud representations is straightforward. Concerning hidden triangles encountered in triangular “soups,” we remark that we do not try to detect such degeneracies and process them as any other triangles. They introduce noise in the density

TABLE 8: DCG and NN scores for the combination of density-based descriptors.

		Sr	St	Sc	[Sr,St]	[Sr,Sc]	[St,Sc]	[Sr,St,Sc]
PSB	DCG	0.533	0.543	0.533	0.599	0.579	0.585	0.607
	NN	0.500	0.527	0.487	0.606	0.572	0.584	0.615
SCUdb	DCG	0.708	0.712	0.732	0.731	0.742	0.744	0.746
	NN	0.745	0.754	0.733	0.788	0.776	0.774	0.786

TABLE 9: General performances of histogram and density-based descriptors.

Descriptor		NN	FT	ST	E	DCG	NDCG
PSB	[Sr,St,Sc]	0.615	0.339	0.434	0.251	0.607	0.214
	[Sr,St]	0.606	0.333	0.423	0.245	0.599	0.199
	3DHT	0.588	0.311	0.396	0.230	0.577	0.154
	D2	0.363	0.168	0.245	0.145	0.448	-0.103
	EGI	0.311	0.165	0.245	0.145	0.438	-0.124
	CAH	0.332	0.159	0.229	0.137	0.433	-0.133
	D1	0.256	0.119	0.185	0.107	0.397	-0.207
SCUdb	[Sr,St,Sc]	0.786	0.518	0.617	0.355	0.746	0.106
	[St,Sc]	0.774	0.513	0.622	0.355	0.744	0.103
	3DHT	0.778	0.485	0.603	0.336	0.727	0.079
	CAH	0.678	0.427	0.536	0.309	0.681	0.010
	D1	0.643	0.366	0.486	0.272	0.646	-0.042
	D2	0.643	0.355	0.467	0.264	0.643	-0.048
	EGI	0.489	0.252	0.349	0.203	0.535	-0.207

estimation but not to the extent to alter the density-based descriptor drastically. Furthermore, hidden triangles present in PSB remain in small proportion and SCUdb models are manifold and free of hidden triangles.

Our framework should be viewed as an application of kernel density estimation [13, 14] with either variable (triangle or mesh levels) or fixed (database level) bandwidth parameters selection [25]. We have also demonstrated that density-based descriptors are much more discriminative in retrieval when the bandwidth parameters are set at database level as compared to mesh or triangle level setting. We think that the database level strategy smoothes out individual shape details and emphasizes global shape properties as appropriate for object retrieval and classification tasks; while the other two options, especially the triangle level strategy, result in an overfitting of the feature density and hamper the descriptor's discrimination ability. Furthermore, the computational advantage of density-based descriptors enabled by FGT with a database-dependent bandwidth matrix is very promising for practical online applications.

When combined together, the multivariate density-based 3D shape descriptors introduced in this work outperform the existing histogram-based techniques in the literature. The retrieval competition took place on two databases, PSB and SCUdb, which are fundamentally different in semantic content and mesh quality. In addition, the performance advantage of density-based descriptors over its competitors is not limited to histogram-based ones, as shown in the more

general comparison where our [Sr,St,Sc]-descriptor reaches the top position in the category of purely 3D descriptors reported in [5]. As a side remark, based on nearest-neighbor scores of our descriptors, we conjecture that they would also perform well in recognition applications.

In summary, a general framework using KDE has been developed, that covers existing and novel descriptors. Our method enables the use of arbitrary one- or multidimensional surface features for retrieval, recognition, and classification of 3D objects. Future research will concentrate on potential improvements of decision fusion. For example, several retrievers can operate in parallel and one can consider rank-weighted reordering of the retrieved objects. A second natural avenue of research is in the direction of second-order features. We will tackle the problem of designing second-order features that would serve as natural proxies for curvature-like quantities. Curvature is in fact difficult to work with because of the estimation inaccuracies involved in its computation. Nevertheless, it can be conjectured that the kernel-based approach, thanks to its smoothing behavior, may be useful in deriving curvature-driven 3D shape descriptors. One of our future objectives is thus to arrive at an exhaustive set of first- and second-order features and to discover computational limits of the density-based approach. A side issue is to render the proposed descriptors more effective in discrimination and more efficient in terms of storage size by adequately sampling the local feature domains for target evaluation points. A further question that should be considered is to which extent

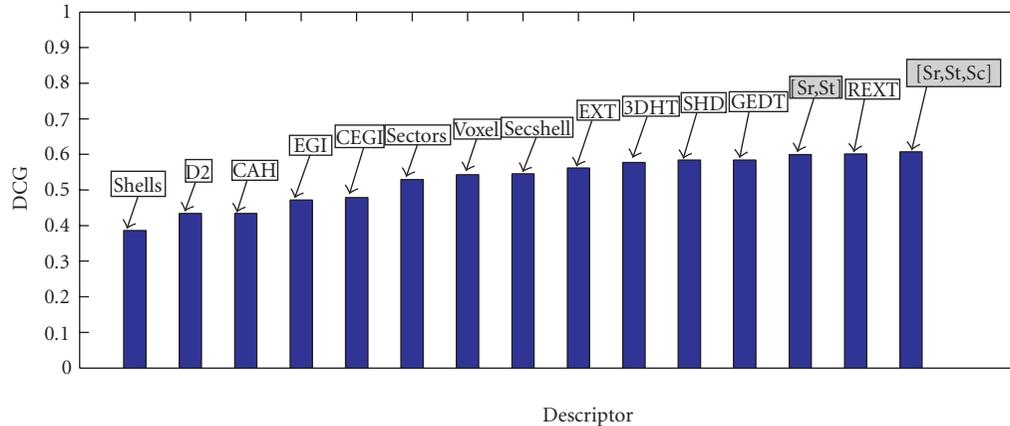


FIGURE 11: Comparison of 3D shape descriptors on PSB test set. (Except CAH, 3DHT, and our descriptors, DCG values are taken from [5].)

the combination of the available features can be exploited, that is, how large the feature dimension of the multivariate densities can be.

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## Special Issue on Human-Activity Analysis in Multimedia Data

### Call for Papers

Many important applications of multimedia revolve around the detection of humans and the interpretation of human behavior, for example, surveillance and intrusion detection, automatic analysis of sports videos, broadcasts, movies, ambient assisted living applications, video conferencing applications, and so forth. Success in this task requires the integration of various data modalities including video, audio, and associated text, and a host of methods from the field of machine learning. Additionally, the computational efficiency of the resulting algorithms is critical since the amount of data to be processed in videos is typically large and real-time systems are required for practical implementations.

Recently, there have been several special issues on the human detection and human-activity analysis in video. The emphasis has been on the use of video data only. This special issue is concerned with contributions that rely on the use of multimedia information, that is, audio, video, and, if available, the associated text information.

Papers on the following and related topics are solicited:

- Video characterization, classification, and semantic annotation using both audio and video, and text (if available).
- Video indexing and retrieval using multimedia information.
- Segmentation of broadcast and sport videos based on audio and video.
- Detection of speaker turns and speaker clustering in broadcast video.
- Separation of speech and music/jingles in broadcast videos by taking advantage of multimedia information.
- Video conferencing applications taking advantage of both audio and video.
- Human mood detection, and classification of interactivity in duplexed multimedia signals as in conversations.
- Human computer interaction, ubiquitous computing using multimedia.
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## Special Issue on

# Signal Processing for Location Estimation and Tracking in Wireless Environments

### Call for Papers

In recent years, the proliferation of mobile computing devices and wireless technologies has fostered a growing interest in location-aware systems and services. The availability of location information on objects and human beings is critical in many military and civilian applications such as emergency call services, tracking of valuable assets, monitoring individuals with special needs in assisted living facilities, location-assisted gaming (e.g., Geocaching), etc.

Existing positioning systems can be categorized based on whether they are intended for indoor or outdoor applications. Within both of these application areas, there are two major categories of position estimation techniques, as discussed below.

- *Geometric techniques*—Position is estimated by exploiting time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA) or other information derived from the relationship between the geometry of an array of receivers and the modeled propagation characteristics of the transmitted signal.
- *Mapping approaches*—Position is estimated based on comparison of local measurements to a “map” of expected distribution of the measured values. For example, in a wireless LAN application, received signal strength (RSS) might be observed either at the location of the client or at a remote reference point. Mapping approaches are also known as location fingerprinting.

Although geometric approaches have the potential to achieve higher precision than mapping approaches, they generally require direct-path signal reception or accurate environmental information at the receiver and often perform poorly in complex multipath environments. On the other hand, estimation accuracy of mapping approaches is limited by both the accuracy of the reference map and the accuracy of observed measurements. Furthermore, frequent and extensive site-survey measurements are often needed to

accommodate the time varying nature of wireless channels, structural changes in the environment, and upgrades of wireless infrastructure.

In addition to snapshots of AOA, TOA, TDOA or RSS measurements, motion models or prior knowledge of structural constraints can often be used to enhance location estimation accuracy for mobile objects by “tracking” location estimates over time. Trackers that integrate such information into the computation of location estimates are generally implemented using techniques such as Kalman filters, particle filters, Markov chain Monte Carlo methods, etc.

The purpose of the proposed special issue is to present a comprehensive picture of both the current state of the art and emerging technologies in signal processing for location estimation and tracking in wireless environments. Papers are solicited on all related aspects from the point of view of both theory and practice. Submitted articles must be previously unpublished and not concurrently submitted for publication on other journals.

Topics of interest include (but are not limited to):

- Received signal strength (RSS), angle-of-arrival (AOA), and time-based location estimation
- Ultrawideband (UWB) location estimation
- Bayesian location estimation and tracking
- Pattern recognition and learning theory approaches to location estimation
- Applications of expectation-maximization (EM) and Markov chain Monte Carlo (MCMC) techniques
- Applications of electromagnetic propagation modeling to location estimation
- Mitigation of errors due to non-line-of-sight propagation
- System design and configuration
- Performance evaluation, performance bounds, and statistical analysis

- Computational complexity and distributed computation
- Distributed location estimation
- Synchronization issues
- Testbed implementation, real-world deployment, and measurement

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# Special Issue on Track Before Detect Algorithms

## Call for Papers

Seamless detection and tracking schemes are able to integrate unthresholded (or below target detection threshold) multiple sensor responses over time to detect and track targets in low signal-to-noise ratio (SNR) and high clutter scenarios. These schemes, also called “track-before-detect (TBD)” algorithms are especially suitable for tracking weak targets that would only very rarely cross a standard detection threshold as applied at the sensor level.

Thresholding sensor responses result in a loss of information. Keeping this information allows some TBD approaches to deal with the classical data association problem effectively in high clutter and low SNR situations. For example, in detection scenarios with simultaneous activation/illumination from different signal sources this feature allows the application of triangulation techniques, where in the case of contact tracking approaches essential information about weak targets would often be lost because these targets did not produce signals that cross the normal detection threshold. Extending this example to a multi-sensor network scenario, a TBD algorithm that can use unthresholded (or below threshold) data has the potential to show improved performance compared to an algorithm that relies on thresholded data. In low SNR situations, this can substantially increase performance particularly in the case of a dense multi-target scenario.

Naturally, TBD algorithms consume high computational processing power: An efficient realization and coding of the TBD scheme is mandatory.

Another issue that arises when using the TBD scheme is the quality of the sensor model: Practical experience with thresholded data shows that a coarser modelling of the likelihood function might be sufficient and often leads to robust algorithms. How much have these sensor models to be improved in order to allow the TBD algorithms to exploit the information provided with the unthresholded data?

TBD algorithms that are well known to the tracking community are the likelihood ratio detection and tracking (LRDT), maximum likelihood probabilistic data association (MLPDA), maximum likelihood probabilistic multihypothesis tracking (MLPMHT), Houghtransform based methods

and dynamic programming techniques; also related are the probability hypothesis density (PHD), the histogram probabilistic multi-hypothesis tracking (H-PMHT) algorithms, and, of course, various particle filter approaches. Some of these algorithms are capable of tracking extended targets and performing signal estimation in multi-sensor measurements.

The aim of this special issue is to focus on recent developments in this expanding research area. The special issue will focus on one hand on the development and comparison of algorithmic approaches, and on the other hand on their currently ever-widening range of applications such as in active or passive surveillance scenarios (e.g. for object tracking and classification with image and video based sensors, or scenarios involving chemical, electromagnetic and acoustic sensors). Special interest lies in multi-sensor data fusion and/or multi-target tracking applications.

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## Special Issue on

# Advanced Signal Processing and Pattern Recognition Methods for Biometrics

### Call for Papers

Biometric identification has established itself as a very important research area primarily due to the pronounced need for more reliable and secure authentication architectures in several civilian and commercial applications. The recent integration of biometrics in large-scale authentication systems such as border control operations has further underscored the importance of conducting systematic research in biometrics. Despite the tremendous progress made over the past few years, biometric systems still have to reckon with a number of problems, which illustrate the importance of developing new biometric processing algorithms as well as the consideration of novel data acquisition techniques. Undoubtedly, the simultaneous use of several biometrics would improve the accuracy of an identification system. For example the use of palmprints can boost the performance of hand geometry systems. Therefore, the development of biometric fusion schemes is an important area of study. Topics related to the correlation between biometric traits, diversity measures for comparing multiple algorithms, incorporation of multiple quality measures, and so forth need to be studied in more detail in the context of multibiometrics systems. Issues related to the individuality of traits and the scalability of biometric systems also require further research. The possibility of using biometric information to generate cryptographic keys is also an emerging area of study. Thus, there is a definite need for advanced signal processing, computer vision, and pattern recognition techniques to bring the current biometric systems to maturity and allow for their large-scale deployment.

This special issue aims to focus on emerging biometric technologies and comprehensively cover their system, processing, and application aspects. Submitted articles must not have been previously published and must not be currently submitted for publication elsewhere. Topics of interest include, but are not limited to, the following:

- Fusion of biometrics
- Analysis of facial/iris/palm/fingerprint/hand images
- Unobtrusive capturing and extraction of biometric information from images/video
- Biometric identification systems based on face/iris/palm/fingerprint/voice/gait/signature

- Emerging biometrics: ear, teeth, ground reaction force, ECG, retina, skin, DNA
- Biometric systems based on 3D information
- User-specific parameterization
- Biometric individuality
- Biometric cryptosystems
- Quality measure of biometrics data
- Sensor interoperability
- Performance evaluation and statistical analysis

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Manuscript Due	May 1, 2007
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Final Manuscript Due	December 1, 2007
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## Special Issue on Signal Processing for Data Converters

### Call for Papers

Data converters (ADCs and DACs) ultimately limit the performance of today's communication systems. New concepts for high-speed, high-resolution, and power-aware converters are therefore required, which also lead to an increased demand for high-speed and high-resolution sampling systems in the measurement industry. Present converter technologies operate on their limits, since the downscaling of IC technologies to deep submicron technologies makes their design increasingly difficult. Fortunately, downscaling of IC technologies allows for using additional chip area for digital signal processing algorithms with hardly any additional costs. Therefore, one can use more elaborate signal processing algorithms to improve the conversion quality, to realize new converter architectures and technologies, or to relax the requirements on the analog design. Pipelined ADCs constitute just one example of converter technology where signal processing algorithms are already extensively used. However, time-interleaved converters and their generalizations, including hybrid filter bank-based converters and parallel sigma-delta-based converters, are the next candidates for digitally enhanced converter technologies, where advanced signal processing is essential. Accurate models constitute one foundation of digital corrected data converters. Generating and verifying such models is a complex and time-consuming process that demands high-performance instrumentation in conjunction with sophisticated software defined measurements.

The aim of this special issue is to bring forward recent developments on signal processing methods for data converters. It includes design, analysis, and implementation of enhancement algorithms as well as signal processing aspects of new converter topologies and sampling strategies. Further, it includes design, analysis, and implementation of software defined measurements for characterization and modeling of data converters.

Topics of interest include (but are not limited to):

- Analysis, design, and implementation of digital algorithms for data converters
- Analysis and modeling of novel converter topologies and their signal processing aspects
- Digital calibration of data converters
- Error identification and correction in time-interleaved ADCs and their generalizations
- Signal processing for application-specific data converters (communication systems, measurement systems, etc.)
- New sampling strategies
- Sampling theory for data converters
- Signal processing algorithms for data converter testing
- Influence of technology scaling on data converters and their design
- Behavioral models for converter characterization
- Instrumentation and software defined measurements for converter characterization

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## Special Issue on Distributed Space-Time Systems

### Call for Papers

Diversity is a powerful technique to mitigate channel fading and to improve robustness to cochannel interference in a wireless network. Space-time wireless systems traditionally use multiple colocated antennas at the transmitter and receiver along with appropriate signal design (also known as space-time coding) to realize spatial diversity in the link. Typically this diversity can augment any frequency and time diversity available to the receiver. Multiple antennas also offer the ability to use spatial multiplexing to dramatically increase the data rate.

A recent development in this area aims at dispensing with the need for colocated antennas. Popularly known as the cooperative diversity technique, this uses the antennas at multiple user terminals in a network in the form of a virtual antenna array to realize spatial diversity in a distributed fashion. Such techniques create new challenges in the design of wireless systems.

The purpose of this call for papers is to address some of these challenges such as new protocols for cooperative diversity, cross-layer design, cooperative multiplexing, space-time coding for distributed antennas, cooperative channel estimation and equalization, selecting the right users for participating in a cooperative network, modulation specific issues like OFDMA and CDMA, and distributed space-time processing for sensor networks.

Papers on the following and related topics are solicited for this special issue:

- New protocols for cooperative diversity systems
- Cross-layer protocol design
- Signal design for distributed space-time systems
- Cooperative channel estimation and equalization
- Cooperative MIMO systems
- Distributed space-time processing for sensor networks
- Power allocation in distributed space-time systems
- Fast algorithms and efficient architectures for virtual MIMO receivers
- Energy efficient relay network architectures

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## Special Issue on

# Cooperative Localization in Wireless Ad Hoc and Sensor Networks

### Call for Papers

One of the major requirements for most applications based on wireless ad hoc and sensor networks is accurate node localization. In fact, sensed data without position information is often less useful.

Due to several factors (e.g., cost, size, power), only a small fraction of nodes obtain the position information of the anchor nodes. In this case, a node has to estimate its position without a direct interaction with anchor nodes and a cooperation between nodes is needed in a multihop fashion. In some applications, none of the nodes are aware of their absolute position (anchor-free) and only relative coordinates are estimated instead.

Most works reported in the literature have studied cooperative localization with the emphasis on algorithms. However, very few works give emphasis on the localization as estimation or on the investigation of fundamental performance limits as well as on experimental activities. In particular, the fundamental performance limits of multihop and anchor-free positioning in the presence of unreliable measurements are not yet well established. The knowledge of such limits can also help in the design and comparison of new low-complexity and distributed localization algorithms. Thus, measurement campaigns in the context of cooperative localization to validate the algorithms as well as to derive statistical models are very valuable.

The goal of this special issue is to bring together contributions from signal processing, communications and related communities, with particular focus on signal processing, new algorithm design methodologies, and fundamental limitations of cooperative localization systems. Papers on the following and related topics are solicited:

- anchor-based and anchor-free distributed and cooperative localization algorithms that can cope with unreliable range measurements
- derivation of fundamental limits in multihop and anchor-free localization scenarios

- new localization algorithms design methodologies based, for example, on statistical inference and factor graphs
- low-complexity and energy-efficient distributed localization algorithms
- distributed ranging and time synchronization techniques
- measurement campaigns and statistical channel modeling
- algorithm convergence issues
- UWB systems
- localization through multiple-antenna systems
- experimental results

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# Special Issue on Information Theoretic Methods for Bioinformatics

## Call for Papers

Information theoretic methods for modeling are at the center of the current efforts to interpret bioinformatics data. The high pace at which new technologies are developed for collecting genomic and proteomic data requires a sustained effort to provide powerful methods for modeling the data acquired. Recent advances in universal modeling and minimum description length techniques have been shown to be well suited for modeling and analyzing such data. This special issue calls for contributions to modeling of data arising in bioinformatics and systems biology by information theoretic means. Submissions should address theoretical developments, computational aspects, or specific applications. Suitable topics for this special issue include but are not limited to:

- Normalized maximum-likelihood (NML) universal models
- Minimum description length (MDL) techniques
- Microarray data modeling
- Denoising of genomic data
- Pattern recognition
- Data compression-based modeling

Authors should follow the EURASIP JBSB manuscript format described at <http://www.hindawi.com/journals/bsb/>. Prospective authors should submit an electronic copy of their complete manuscript through the EURASIP JBSB's manuscript tracking system at <http://www.hindawi.com/mts/>, according to the following timetable.

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## Special Issue on Multimedia over Wireless Networks

### Call for Papers

#### Scope

In recent years there has been a tremendous increase in demand for multimedia delivered over wireless networks. The design and capabilities of the mobile devices and the services being offered reflect the increase in multimedia usage in the wireless setting. Applications that are in the process of becoming essential to users include video telephony, gaming, or TV broadcasting. This trend creates great opportunities for identifying new wireless multimedia applications, and for developing advanced systems and algorithms to support these applications. Given the nature of the channel and of the mobile devices, issues such as scalability, error resiliency, and energy efficiency are of great importance in applications involving multimedia transmission over wireless networks.

The papers in this issue will focus on state-of-the-art research on all aspects of wireless multimedia communications. Papers showing significant contributions are solicited on topics including but are not limited to:

- Error resilience and error concealment algorithms
- Rate control for wireless multimedia coding
- Scalable coding and transmission
- Joint source-channel coding
- Joint optimization of power consumption and rate-distortion performance
- Wireless multimedia traffic modeling
- Wireless multimedia streaming
- Wireless multimedia coding
- QoS for wireless multimedia applications
- Distributed multimedia coding

Authors should follow the EURASIP Journal on Wireless Communications and Networking manuscript format described at <http://www.hindawi.com/journals/wcn/>. Prospective authors should submit an electronic copy of their complete manuscript through the EURASIP Journal on Wireless Communications and Networking's Manuscript Tracking System at <http://www.hindawi.com/mts/>, according to the following timetable:

Manuscript Due	March 1, 2007
Acceptance Notification	July 1, 2007
Final Manuscript Due	October 1, 2007
Publication Date	4th Quarter, 2007

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# Special Issue on Image and Video Processing for Disability

## Call for Papers

New technologies represent a great opportunity for the improvement of life and independent living of the disabled and elder people. Over the last decade, active researches have produced novel algorithms for blind, deaf, mute people or for people with severe motor disabilities. These researches are strongly related with the development of new dedicated systems for human-computer interactions.

Whatever the kind of handicap, image processing can provide a significant help for disability compensation to avoid the gap increasing between disabled and nondisabled people with respect to the new technologies.

Researches for new systems for disabled people are multidisciplinary research from engineering sciences (computer science, HCI, automatic, electronics, etc.) and human sciences (psychology, cognition, etc.). Here we are focusing on researches involving image and video processing for disability. However, multimodal signals-based systems can be considered.

The goal of this special issue is to provide original contributions in the field of image and video processing for disability.

Topics of interest include (but are not limited to):

- Eye-gaze analysis and interpretation
- Head motion analysis
- Human behavior modeling
- HCI for disabled people
- Hand-gesture analysis and interpretation
- Sign language recognition
- Modality replacement
- Multimodal systems for disabled
- Facial expressions interpretation

In each case, works should be related to an application dedicated to disabled or elder people's help.

Authors should follow the EURASIP JIVP manuscript format at <http://www.hindawi.com/journals/ivp/>. Prospective authors should submit an electronic copy of their complete manuscripts through the EURASIP JIVP manuscript tracking system at <http://www.hindawi.com/mts/>, according to the following timetable:

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Acceptance Notification	April 1, 2007
Final Manuscript Due	June 1, 2007
Publication Date	3rd Quarter, 2007

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# Special Issue on Anthropocentric Video Analysis: Tools and Applications

## Call for Papers

Humans are a basic entity in most videos. Lately, there has been increased interest in devising automated video analysis algorithms that aim to extract, efficiently describe, and organize information regarding the state or state transition of individuals (identity, emotional state, activity, position and pose, etc), interactions between individuals (dialogue, gestures, engagement into collaborative or competitive activities like sports), physical characteristics of humans (anthropometric characteristics, 3D head/body models), and so forth. Such information can be utilized in a multitude of important applications that include, but are not limited to:

- Human computer interaction, ubiquitous computing
- Video characterization, classification, and semantic annotation
- Video indexing and retrieval
- Temporal video segmentation (shot and scene boundary detection) and summarization
- Intelligent video surveillance, access control, and other security related applications

High quality and original contributions on the following (nonexhaustive) list of topics related to anthropocentric video analysis and its applications are solicited:

- Detection and tracking of humans or human body parts
- Action recognition and human behavior analysis
- Emotional state recognition
- Anthropocentric video characterization, semantic annotation, indexing, retrieval, temporal segmentation and summarization
- Efficient description schemes for anthropocentric video information
- Dialogue detection, LiP activity detection, visual speech recognition
- Hand gesture recognition
- 3D modeling of humans
- Person verification and recognition

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# IEEE ICME 2007 Call for Papers

## 2007 International Conference on Multimedia & Expo (ICME)

July 2-5, 2007

Beijing International Convention Center, Beijing, China



Sponsored by: Circuits and Systems Society, Communications Society, Computer Society, and Signal Processing Society.

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**IEEE International Conference on Multimedia & Expo** is a major annual international conference with the objective of bringing together researchers, developers, and practitioners from academia and industry working in all areas of multimedia. ICME serves as a forum for the dissemination of state-of-the-art research, development, and implementations of multimedia systems, technologies and applications. ICME is co-sponsored by four IEEE societies including the Circuits and Systems Society, the Communications Society, the Computer Society, and the Signal Processing Society. The conference will feature world-class plenary speakers, exhibits, special sessions, tutorials, and paper presentations.

Prospective authors are invited to submit a four-page paper in double-column format including authors' names, affiliations, and a short abstract. Only electronic submissions will be accepted. Topics include but are not limited to:

- Audio, image, video processing
- Virtual reality and 3-D imaging
- Signal processing for media integration
- Multimedia communications and networking
- Multimedia security and content protection
- Multimedia human-machine interface and interaction
- Multimedia databases
- Multimedia computing systems and appliances
- Hardware and software for multimedia systems
- Multimedia standards and related issues
- Multimedia applications
- Multimedia and social media on the Internet

A number of awards will be presented to the Best Papers and Best Student Papers at the conference. Participation for special sessions and tutorial proposals are encouraged.

### SCHEDULE

- Special Session Proposals Due: **December 1, 2006**
- Tutorial Proposals Due: **December 1, 2006**
- Regular Paper Submissions Due: **January 5, 2007**
- Notification of Acceptance: **March 19, 2007**
- Camera-Ready Papers Due: **April 16, 2007**

Check the conference website <http://www.icme2007.org> for updates.

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# 3DTV CONFERENCE 2007

THE TRUE VISION - CAPTURE, TRANSMISSION AND DISPLAY OF 3D VIDEO

May 7-9, 2007, KICC Conference Center, Kos Island, Greece

## First Call For Papers

Creating exact 3D moving images as ghost-like replicas of 3D objects has been an ultimate goal in video science. Capturing 3D scenery, processing the captured data for transmission, and displaying the result for 3D viewing are the main functional components. These components encompass a wide range of disciplines: imaging and computer graphics, signal processing, telecommunications, electronics, optics and physics are needed.

The objective of the **3DTV-Conference** is to bring together researchers and developers from academia and industry with diverse experience and activity in distinct, yet complementary, areas so that full scale 3D video capabilities are seamlessly integrated.

## Topics of Interest

### 3D Capture and Processing

- 3D time-varying scene capture technology
- Multi-camera recording
- 3D photography algorithms
- Synchronization and calibration of camera arrays
- 3D view registration
- Multi-view geometry and calibration
- Holographic camera techniques
- 3D motion analysis and tracking
- Surface modeling for 3-D scenes
- Multi-view image and 3D data processing

### 3D Transmission

- Systems, architecture and transmission aspects of 3D
- 3D streaming
- Error-related issues and handling of 3d video
- Hologram compression
- Multi-view video coding
- 3D mesh compression
- Multiple description coding for 3D
- Signal processing for diffraction and holographic 3DTV

### 3D Visualization

- 3D mesh representation
- Texture and point representation
- Object-based representation and segmentation
- Volume representation
- 3D motion animation
- Dense stereo and 3D reconstruction
- Stereoscopic display techniques
- Holographic display technology
- Reduced parallax systems and integral imaging
- Underlying optics and VLSI technology
- Projection and display technology for 3D videos
- Human factors

### 3D Applications

- 3D imaging in virtual heritage and virtual archaeology
- 3D Teleimmersion and remote collaboration
- Augmented reality and virtual environments
- 3D television, cinema, games and entertainment
- Medical and biomedical applications
- 3D Content-based retrieval and recognition
- 3D Watermarking

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### Webmaster

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Centre for Research and  
Technology Hellas, GR

## Paper Submission

Prospective contributors are invited to submit full papers electronically using the on-line submission interface, following the instructions available at <http://www.3dttv-con.org>. Papers should be in Adobe PDF format, written in English, with no more than four pages including figures, using a font size of 11. Conference proceedings will be published online by the IEEE.

## Important Dates

1 December 2006  
15 December 2006  
9 February 2007  
2 March 2007

Special sessions and tutorials proposals  
Regular Paper submission  
Notification of acceptance  
Submission of camera-ready papers



3DTV NoE



ITI-CERTH



Information Society  
Technologies



Institute of Electrical and  
Electronics Engineers



European Association  
for Signal and  
Image Processing



MPEG-IF



**The International ITG /  
IEEE Workshop on Smart Antennas  
WSA 2007  
February 26-27, 2007  
Vienna**



## Call for Papers

The International ITG / IEEE Workshop on Smart Antennas WSA 2007 provides a forum for presentation of the most recent research on smart antennas. The objective is to continue, accelerate, and broaden the momentum already gained with a series of ITG Workshops held since 1996: Munich and Zurich'96, Vienna and Kaiserslautern'97, Karlsruhe' 98, Stuttgart'99, Ilmenau'01, Munich'04, Duisburg'05, and Ulm'06. This call for papers intends to solicit contributions on latest research of this key technology for wireless communication systems.

### Workshop topics include, but are not limited to:

- Antennas for beamforming and diversity
- Channel measurements
- Spatial channel modeling
- Beamforming
- Diversity concepts
- Space-time processing
- Space-time codes
- MIMO Systems
- Multicarrier MIMO
- Multiuser MIMO
- Cooperative and sensor networks
- Crosslayer optimisation
- Radio resource management
- Cellular systems
- Link, system and network level simulations
- Hard- and software implementation issues

There will be oral as well as poster presentations.

The workshop will be jointly organized by the Institute of Communications and Radio Frequency at Vienna University of Technology and the ftw. Telecommunications Research Center Vienna in cooperation with the VDE, ÖVE, and the IEEE on February 26-27, 2007 in Vienna, Austria

### Organizers and Workshop Chairs

Markus Rupp,  
E-Mail: [mrupp@nt.tuwien.ac.at](mailto:mrupp@nt.tuwien.ac.at)  
Christoph Mecklenbräuer,  
E-Mail: [cfm@ftw.at](mailto:cfm@ftw.at)

Information about the workshop can soon be found at: <http://www.ftw.at/>

### Technical program committee

Jørgen Bach-Andersen	David Gesbert	Michael Meurer	Werner Teich
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# 5th International Symposium on Image and Signal Processing and Analysis ISPA 2007

September 27-29, 2007, Istanbul, Turkey



<http://www.isispa.org>



## Call for Papers

The 5th International Symposium on Image and Signal Processing and Analysis (ISPA 2007) will take place in Istanbul, Turkey, from September 27-29, 2007. The scientific program of the symposium consists of invited lectures, regular papers, and posters. The aim of the symposium is to foster interaction of researchers and exchange of new ideas. Prospective authors are invited to submit their manuscripts reporting original work, as well as proposals for special sessions.

### Co-Operations and Co-Sponsorships

- European Association for Signal Processing (EURASIP)
- IEEE Region 8\*

### Symposium Topics

- |                                     |                      |
|-------------------------------------|----------------------|
| A. Image and Video Processing       | D. Signal Processing |
| B. Image and Video Analysis         | E. Signal Analysis   |
| C. Image Formation and Reproduction | F. Applications      |

For a detailed list of subtopics please visit ISPA 2007 web site.

### Important Dates

Submission of full paper: February 15, 2007

Notification of acceptance/rejection: April 15, 2007

Submission of camera-ready papers and registration: May 15, 2007

### Symposium Venue

Located in the center of the Old World, Istanbul is one of the world's great cities famous for its historical monuments and scenic beauties. It is the only city in the world which spreads over two continents: it lies at a point where Asia and Europe are separated by a narrow strait - the Bosphorus. Istanbul has been the cradle for many civilizations for over 2500 years and has a very rich history. It has been the capital of three great empires, the Roman, Byzantine and Ottoman empires, and for more than 1,600 years over 120 emperors and sultans ruled the world from here. Istanbul is the heart of Turkey with respect to entertainment, culture, education, shopping, imports and exports, tourism and the arts. The symposium will be organized in the congress center of the Bogazici University.

### Paper Submission Procedure

Papers including title, author list and affiliations, figures, results, and references should not exceed six A4 pages. Detailed instructions for electronic submission are available on the ISPA web site. All papers will be subject to a peer-review process with at least two reviewers. All accepted papers will be published in the symposium proceedings in book form and on CD-ROM, which will be available through IEEE Publications Center and in IEEEExplore digital library.

### Call for Special Session Proposals

Prospective organizers of special sessions are invited to send proposals to Special Session Co-Chairs, according to instructions provided on the ISPA web site. The aim of a special session is to provide an overview of the state-of-the-art and current research directions in specific fields of image and signal processing and analysis.

### Best Student Paper Award

Best Student Paper Award in the amount of 300 EUR will be given to a student author. The student's name must appear first on the paper and the paper must be presented at the symposium to be eligible for the award.

\* request pending



# ISSPA 2007

International Symposium on Signal Processing and its Applications

in conjunction with the International Conference on  
Information Sciences, Signal Processing and their Applications

12 – 15 February 2007, Millennium Hotel, Sharjah, U.A.E.

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University of Sharjah, UAE  
The University of Queensland, Australia

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Tampere University of Technology, Finland

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University of California, Santa Barbara, USA

Special Sessions

**M. Cheriet, Chair**  
University of Quebec, Canada

**M. Barkat, Co-Chair**  
American University of Sharjah, UAE

**L. Karam, Co-Chair**  
Arizona State University, USA

Tutorials

**M. El-Tarhuni**  
American University of Sharjah, UAE

Industry Liaison

**H. Al-Ahmad**  
Etisalat University College, UAE

Publications

**M. Al-Qutayri**  
Etisalat University College, UAE

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**K. Al-Midfa**  
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University of Sharjah, UAE

Finance & Registration

**C. B. Yahya and A. Darwish**  
University of Sharjah, UAE

Local Arrangements

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University of Sharjah, UAE

Social Events

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University of Sharjah, UAE  
**H. A. Al-Hamady**  
Etisalat University College, UAE

Web and IT

**B. Soudan**  
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**S. Anderson, Australia**  
DSTO, Australia

**S. Furui, Asia and Pacific**  
Tokyo Institute of Technology, Japan

**M. Gabbouj, Europe**  
Tampere University of Technology, Finland

**M. Jaidane, Africa**  
ENIT, Tunisia

**Y. Zhang, America**  
Villanova University, USA



## Call For Participation

**ISSPA 2007** marks the 20th anniversary of launching the first ISSPA in 1987 in Brisbane, Australia. Since its inception, ISSPA has provided, through a series of 8 symposia, a high quality forum for engineers and scientists engaged in research and development of Signal and Image Processing theory and applications. Effective 2007, ISSPA will extend its scope to add the new track of information sciences. Hence, the intention that the previous full name of ISSPA is replaced after 2007 by the following new full name:  
*International Conference on Information Sciences, Signal Processing and their Applications.* **ISSPA** is an IEEE indexed conference.

**ISSPA 2007** is organized by the University of Sharjah, College of Engineering, Etisalat University College and the American University of Sharjah.

The regular technical program will run for three days along with an exhibition of signal processing and information sciences products. In addition, tutorial sessions will be held on the first day of the symposium. Presentations will be given in the following topics:

- |  |   |  |
|--|---|--|
| 1. Filter Design Theory and Methods      | 11. Multimedia Signal Processing                        | 21. Signal Processing for Bioinformatics                 |
| 2. Multirate Filtering & Wavelets        | 12. Nonlinear signal processing                         | 22. Signal Processing for Geoinformatics                 |
| 3. Adaptive Signal Processing            | 13. Biomedical Signal and Image Processing              | 23. Biometric Systems and Security                       |
| 4. Time-Frequency/Time-Scale Analysis    | 14. Image and Video Processing                          | 24. Machine Vision                                       |
| 5. Statistical Signal & Array Processing | 15. Image Segmentation and Scene Analysis               | 25. Data visualization                                   |
| 6. Radar & Sonar Processing              | 16. VLSI for Signal and Image Processing                | 26. Data mining  |
| 7. Speech Processing & Recognition       | 17. Cryptology, Steganography, and Digital Watermarking | 27. Sensor Networks and Sensor Fusion                    |
| 8. Fractals and Chaos Signal Processing  | 18. Image indexing & retrieval                          | 28. Signal Processing and Information Sciences Education |
| 9. Signal Processing in Communications   | 19. Soft Computing & Pattern Recognition                | 29. Others   |
| 10. Signal processing in Networking      | 20. Natural Language Processing                         | 30. Special Sessions                                     |

*Prospective authors were invited to submit **full length** (four pages) papers **via the conference website** for presentation in any of the areas listed above (showing area in submission). Submission of proposals for student session, tutorials and sessions on special topics were sent to the conference secretary. All articles submitted to ISSPA 2007 are **peer-reviewed** using a **blind review process** by at least two independent reviewers.*

For more details see

[www.isspa2007.org/](http://www.isspa2007.org/)

Important Deadlines:

**Full Paper Submission:**

October 14, 2006

**Tutorials/Special Sessions Submission:**

October 14, 2006

**Notification of Acceptance:**

December 3, 2006

**Final Accepted Paper Submission:**

December 19, 2006

Conference Secretary

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