

SymPan: 3D Model Pose Normalization via Panoramic Views and Reflective Symmetry

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Abstract

A novel pose normalization method, based on panoramic views and reflective symmetry, is presented. Initially, the surface of a 3D model is projected onto the lateral surface of a circumscribed cylinder, aligned with the primary principal axis of space. Based on this cylindrical projection, a normals' deviation map is extracted and using an octree-based search strategy, the rotation which optimally aligns the primary principal axis of the 3D model and the cylinder's axis is computed. The 3D model's secondary principal axis is then aligned with the secondary principal axis of space in a similar manner. The proposed method is incorporated in a hybrid scheme, that serves as the pose normalization method in a state-of-the-art 3D model retrieval system. The effectiveness of this system, using the hybrid pose normalization scheme, is evaluated in terms of retrieval accuracy and the results clearly show improved performance against current approaches.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling —I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—I.3.8 [Computer Graphics]: Applications—

1. Introduction

In recent years, the increased availability of cheap 3D object acquisition hardware and simplified 3D modelling software has resulted in the creation of massive 3D model datasets that are either publicly available or proprietary (e.g. industrial). This increase of information has also created the need for methods that are both effective and efficient in terms of annotating 3D models and searching over large datasets.

A key step in the pipeline of 3D model retrieval is the uniform pose normalization (also known as alignment) of the 3D models, so that the feature extraction algorithms which follow, are able to achieve a match between the (spatial) characteristics of the 3D models. Furthermore, 3D model alignment is a handy tool for the visualization of large 3D model databases in an effective manner. To achieve normalization, for every 3D model, a corresponding set of normalization transformations (translation, scaling and rotation) in 3D space must be defined.

In most cases, translation and scale normalization can be

achieved by standard techniques. The most frequently used method for performing translation normalization is to position the centroids of 3D models at the origin. Scale normalization can be performed through the definition of a fixed surrounding model (a sphere or a rectangle) within which every 3D model is contained exactly. Rotation normalization (or 3D model alignment), however, is the most difficult part and still under investigation [CVB09, yCO02, Kaz07, PRM*00, Rus07, VSR01]. Although it is relatively easy to perform manual alignment of a 3D model with a fixed number of rotations and acceptable accuracy, the high complexity and the numerous variations of 3D models render the automation of such a procedure difficult.

In this paper we present a novel rotation normalization methodology which produces enhanced results, as attested both visually and via the resulting accuracy on a 3D object retrieval application. In the proposed methodology, the surface of the 3D model is initially projected on the lateral surface of a circumscribed cylinder, aligned with the primary principal axis in space. For each point on the cylin-

der's surface, the angular difference of its normal against a corresponding surface point of the 3D model is computed, thus creating a **Normals' Deviation Map** (NDM). The maximization of the mean value of the NDM will result in the minimization of the angular difference between the 3D model's surface normals and those of its circumscribed cylinder, therefore achieving alignment between the primary principal axis of the 3D model and the corresponding axis of the cylinder. The alignment process is further enhanced by a measure based on the 3D model's symmetry characteristics using an octree-based search strategy. In particular, the NDM image is scanned for a column of vertical symmetry that results in the polar coordinate at which the model exhibits the greatest degree of reflective symmetry. Following the alignment of the 3D model's primary principal axis, a similar search methodology is used for its secondary principal axis. The insight for the proposed approach is that the principal axis of a model often coincides with its axis of symmetry.

The use of reflective symmetry as a feature for pose normalization and 3D model retrieval seems to enhance the results [KFR04], as most of the 3D models exhibit symmetrical properties to some degree. These properties are both distinct between different classes and similar between models of the same class, therefore enhancing the distinctiveness of other commonly used characteristics, such as the spatial distribution and/or surface orientation of the 3D models.

Experimental results of the proposed method show that the qualitative normalization outcome is improved, compared to current approaches. Additionally, when the proposed method is incorporated in a hybrid pose normalization scheme, which takes into account both spatial and angular 3D model distribution properties, as well as symmetry characteristics, it significantly enhances the discriminative power of a 3D model retrieval system.

The remainder of the paper is structured as follows. In Section 2, related work in pose normalization and 3D model retrieval is presented. In Section 3 details of the proposed pose normalization method are given. Section 4 presents experimental results in the course of the method's evaluation and finally, conclusions are drawn in Section 5.

2. Related Work

In this section an overview of the state-of-the-art in pose normalization methods, with particular focus on the alignment phase, is presented. A discussion on the state-of-the-art in 3D model retrieval techniques is also included.

2.1. Pose Normalization

The best-known approach for computing the alignment of 3D models is Principal Component Analysis (PCA) or Karhunen - Loeve transformation [PRM*00, SMK04,

TK99, VSR01, ZP04]. The PCA algorithm, based on the computation of 3D model moments, estimates the principal axes of a 3D model that are used to determine its orientation. Vranic introduced an improvement to the original method, the Continuous PCA (CPCA) algorithm [Vra04, VSR01, Vra05]. CPCA computes the principal axes of a 3D model based on the continuous triangle set. Similar to the CPCA method, Papadakis et al. proposed the Normal PCA (NPCA) algorithm [PPPT07, PPT*08], which computes the principal axes of the 3D model based on the surface normal set.

Kazhdan et al. [KCD*02] define a reflective symmetry descriptor that represents a measure of reflective symmetry for an arbitrary 3D voxel model, for all planes through the model's center of mass. This descriptor is used for finding the main axes of symmetry or to determine that none of them exist in a 3D model. In [PSG*06], Podolak et al. extended this work and introduced a Planar Reflective Symmetry Transform (PRST) that computes a measure of the reflective symmetry of a 3D shape with respect to all possible planes. This measure is used to define the center of symmetry and the principal symmetry axes of the global coordinate system. Using both PCA-alignment and planar reflective symmetry, Chaouch and Verroust - Blondet [CVB09] compute a 3D model's alignment axes and then, using a Local Translational Invariance Cost (LTIC), make a selection of the most suitable ones. Using a rectilinearity measure, Lian et al. [LRS10] attempt to find a 3D model's best rotation by estimating the maximum ratio of its surface area to the sum of its three orthogonal projected areas. Similar to the previous approach, [CVB09], a selection between the proposed and a PCA-based alignment is made.

In [ALD11] Axenopoulos et al. combine the properties of plane reflection symmetry and rectilinearity for achieving alignment. Sfikas et al. [STP11] proposed a 3D model pose normalization method based on the similarity between a 3D model and its symmetric model across a plane of symmetry, thus determining the optimal plane of symmetry of the model. Initially, the axis-aligned minimum bounding box of a rigid 3D model is modified by requiring that the 3D model is also in minimum angular difference with respect to the normals to the faces of its bounding box. To estimate the modified axis-aligned bounding box, a set of predefined planes of symmetry are used and a combined spatial and angular distance, between the 3D model and its symmetric model, is calculated. By minimizing the combined distance, the 3D model fits inside its modified axis-aligned bounding box and alignment with the coordinate system is achieved.

2.2. 3D Model Retrieval

One of the most acknowledged methods for 3D model retrieval, based on the extraction of features from 2D representations of the 3D models, was the Light Field descriptor, proposed by Chen et al. [CTS03]. This descriptor is com-

prised of Zernike moments and Fourier coefficients computed on a set of projections taken at the vertices of a dodecahedron. Lian et al. [LRS10] proposed an enhancement to the Light Field descriptor, by computing the same features on projections taken from the vertices of geodesic spheres generated by the regular unit octahedron. Vranic [Vra04] proposed a shape descriptor where features are extracted from depth buffers produced by six projections of the model, one for each side of a cube which encloses the model. In the same work, the Silhouette-based descriptor is proposed which uses the silhouettes produced by projections on the Cartesian planes.

The GEDT descriptor proposed by Kazhdan et al. [KFR03] is a volumetric representation of the Gaussian Euclidean Distance Transform of a 3D model, expressed by norms of spherical harmonic frequencies. In Papadakis et al. [PPPT07], the CRSP descriptor was proposed which uses the Continuous PCA (CPCA) along with Normals PCA (NPCA) to alleviate the rotation invariance problem and describes a 3D model using a volumetric spherical-function based representation expressed by spherical harmonics. Vranic [Vra05] developed a hybrid descriptor called DESIRE, that consists of the Silhouette, Ray and Depth buffer based descriptors, which are combined linearly by fixed weights. Papadakis et al. [PPT*08] proposed a hybrid descriptor formed by combining features extracted from a depth-buffer and spherical function based representation, with enhanced translation and rotation invariance properties. The advantage of this method is its discriminative power and its minimal space and time requirements. In [KFR04, KCD*02] Kazhdan et al. proposed the planar reflective symmetry descriptor (PRSD), a collection of spherical functions that describes the measure of a model's rotational and reflective symmetry with respect to every axis passing through its center of mass. Extending this work to every possible plane, Podolak et al. presented the planar reflective symmetry transformation (PRST) in [PSG*06].

Chaouch and Verroust - Blondet [CVB09, CVB07] proposed the depth line descriptor, where a 3D model is projected onto the faces of its bounding box giving six depth buffers. Each depth buffer is then decomposed into a set of horizontal and vertical depth lines that are converted to state sequences which describe the change in depth at neighboring pixels. Papadakis et al. in [PPTP10] proposed PANORAMA, a 3D shape descriptor that uses a set of panoramic views of a 3D model which describe the position and orientation of the model's surface in 3D space. For each view, the corresponding 2D Discrete Fourier Transform and the 2D Discrete Wavelet Transform are computed.

3. The Proposed Method

Let us define a projection cylinder as a cylinder whose axis is aligned with the primary principal axis of space (e.g. the Z axis), as described by Papadakis et al. [PPTP10]. To ob-

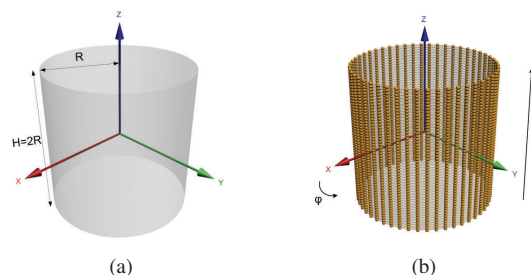


Figure 1: (a) A projection cylinder for the acquisition of a 3D model's panoramic view and (b) the corresponding discretization of its lateral surface to the set of points $s(\phi_u, y_v)$

tain a **Normals' Deviation Map** (NDM) for a 3D model, we project the 3D model onto the lateral surface of a cylinder of radius R and height $H = 2R$, centered at the origin, with its axis parallel to the primary axis of space, see Fig. 1a. We set the value of R to $2 * d_{max}$ where d_{max} is the maximum distance of the model's surface from its centroid. In the following, we parameterize the lateral surface of the cylinder using a set of points $s(\phi, y)$ where $\phi \in [0, 2\pi]$ is the angle in the xy plane, $y \in [0, H]$ and we sample the ϕ and y coordinates at rates $2B$ and B , respectively (we set $B = 360$). Thus we obtain the set of points $s(\phi_u, y_v)$ where $\phi_u = u * 2\pi / (2B)$, $y_v = v * H / B$, $u \in [0, 2B - 1]$ and $v \in [0, B - 1]$. These points are shown in Fig. 1b.

We shall next determine the value at each point $s(\phi_u, y_v)$ of the NDM. The computation is carried out iteratively for $v = 0, 1, \dots, B - 1$, each time considering the set of coplanar $s(\phi_u, y_v)$ points, i.e. a cross section v of the cylinder at height y_v and for each cross section we cast rays from its center c_v in the ϕ_u directions. To capture the orientation of the model's surface, we compute the intersection of each ray with the model's surface and measure the cosine of the angle between the ray and the normal vector to the triangle that is intersected (see Fig. 2). If multiple triangles are intersected by a ray, we take the intersection that is furthest from c_v .

If $ang(\phi_u, y_v)$ denotes the aforementioned angle, then the values of the $s(\phi_u, y_v)$ points are given by:

$$s(\phi_u, y_v) = |\cos(ang(\phi_u, y_v))|^n \quad (1)$$

We take the n th power of $|\cos(ang(\phi_u, y_v))|$, where $n \geq 2$, since this setting enhances the contrast of the produced cylindrical projection. We have experimentally found that setting n to a value in the range $[4, 6]$ gives the best results. Also, taking the absolute value of the cosine is necessary to deal with inconsistently oriented triangles along the model's surface.

The physical interpretation of the NDM is the follow-

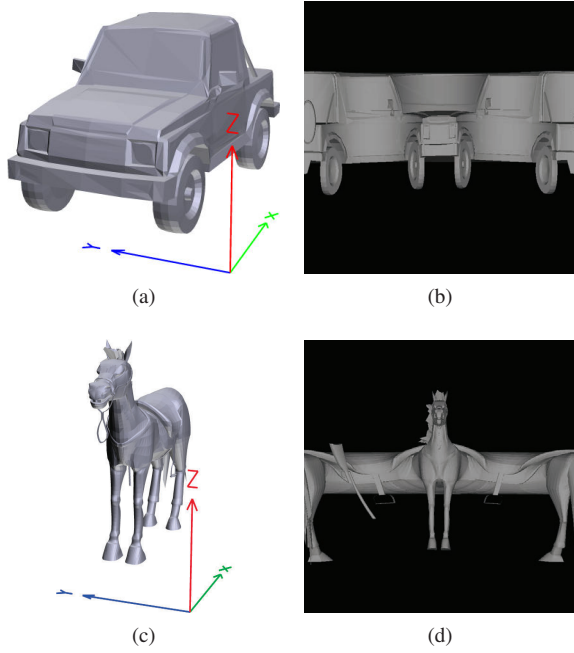


Figure 2: (a),(c) Two example 3D models and (b),(d) their corresponding cylindrical projections capturing the orientation of the surface on the Z-axis.

ing: at each discretized point (ϕ_u, y_v) of the projection image (pixel), the value stored defines the amount of light reflected back from the cylinder's surface to point (ϕ_u, y_v) by the 3D model's surface from a light source located at the same point. The more parallel the 3D model's surface to the surface of the cylinder, the greater the amount of light which is reflected back (thus higher luminance).

To achieve alignment between a 3D model and a projection cylinder, we compute two equally weighted factors: (i) a measure of how parallel the surface of the 3D model is to the lateral surface of the cylinder, as given by the mean value of the NDM and (ii) the degree of reflective symmetry established by the NDM:

$$D = \overline{NDM} + S(NDM) \quad (2)$$

where \overline{NDM} stands for the mean value of the NDM and $S(NDM)$ measures the reflective symmetry of the NDM.

To measure the reflective symmetry of the 3D model a method similar to the one proposed in [ZH02] is followed: define a sliding window of width and height $2n$ and n of the NDM's total width and height, respectively, positioned at the NDM's vertical center (we set $n = 20\%$ pixels). At each window position, the reflective symmetry measured at its central column w , is:

$$SymDiff(w, h) = \frac{1}{n} \sum_{l=1}^n |((w, h) - l) - ((w, h) + l)| \quad (3)$$

$$Sym(w) = 1 - \frac{1}{2n} \sum_{h=\frac{height-n}{2}}^{\frac{height+n}{2}} SymDiff(w, h) \quad (4)$$

where (w, h) denotes the NDM pixel located at column w and row h .

The process is repeated for every sliding window position on the NDM and the maximum $Sym(w)$ value is stored as the NDM's symmetry score. Figure 3 illustrates two example NDM images with the symmetry columns indicated and the corresponding symmetry scores graphs as extracted by the proposed method:

$$S(NDM) = \max\{Sym(w) | w \in 1 : width\} \quad (5)$$

According to Euler's Rotation Theorem, to reach any target frame, a specific sequence of three rotations, that are described by three angles is required. The first two rotations establish a common principal rotation axis between the source and target frames (also known as the 'line of nodes'). The third rotation, about the principal rotation axis, aligns the remaining axes of the reference and target frames [GP01, MR65].

To this end, we use an octree search strategy for the estimation of the two rotations required for the 3D model's principal axis to become aligned with the cylinder's axis:

Rotate the 3D model around the secondary and tertiary principal axes of space by both θ° and $-\theta^\circ$ and compute the symmetry measure D for the resulting NDM image. Set the 3D model's new orientation to the one which results in the maximum value of D . Set $\theta = \theta/2$ and repeat the search process until $\theta = 0.125^\circ$. Initially $\theta = 90^\circ$. During our experiments the algorithm always converged within 20 steps; we used a maximum of 30 steps to guarantee termination.

After the alignment of the 3D model's principal axis, a search on the 3D model's NDM for its secondary principal axis is carried out, based solely on the 3D model's reflective symmetry characteristics. Again, $Sym(w)$ is computed for every column of the aligned model's NDM and the position of the maximum $Sym(w)$ value is stored as the 3D model's secondary principal axis:

$$S_{index}(NDM) = \arg \max\{Sym(w) | w \in 1 : width\} \quad (6)$$

The model is then rotated around its primary principal axis so that its secondary principal axis becomes aligned with the corresponding secondary principal axis of space (i.e. the X axis).

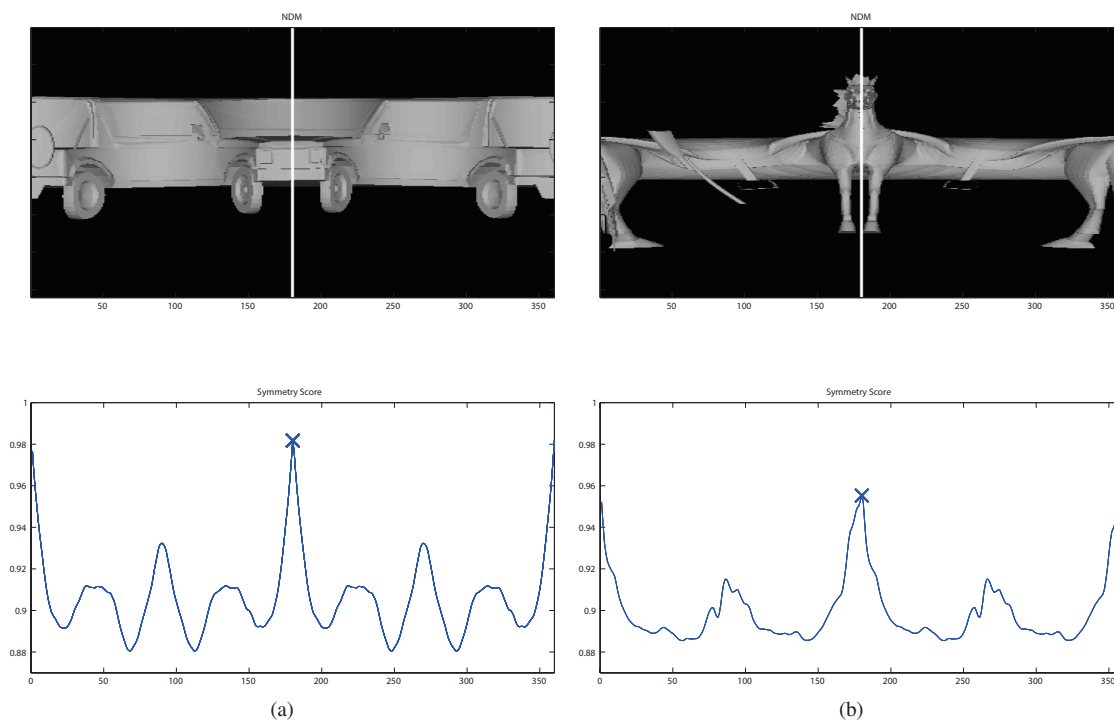


Figure 3: Top row: example NDM images with symmetry column indicated and, bottom row: the corresponding symmetry scores graphs as extracted by the proposed method.

4. Experiments

Evaluating an alignment method directly is inherently difficult as, in the best case, the evaluation may be based on a subjective ground truth alignment that a human operator performed on a dataset. However, since pose normalization procedures are primarily used as a preprocessing step in graphics applications like visualization, reconstruction from broken fragments and 3D object retrieval, it is possible to evaluate the performance of an alignment method through the results of such an application. We have chosen the PANORAMA state-of-the-art 3D object retrieval methodology, by Papadakis et al. [PPTP10] as the evaluation vehicle. The proposed method replaces the NPCA pose normalization method in the existing hybrid scheme.

The dataset, on which the experiments were conducted, is the test subset of the Princeton Shape Benchmark (PSB) [SMKF04]. This dataset is composed of 907 3D models classified into 92 classes. The direct effect of the proposed alignment method can be evaluated by comparing against the original PANORAMA performance. In terms of object retrieval performance, we compare against DLA [CVB09], GSMD+SHD+R [LRS10], ROSy+ [STP11], Lightfield [CTS03], SH-GEDT [KFR03] and DESIRE [Vra05].

Our experimental evaluation is based on Precision-Recall

Table 1: Quantitative measures of SymPan 3D model pose normalization method on PANORAMA, and the corresponding 3D object retrieval methods illustrated in Fig 4. All measures are normalized.

Method	NN	FT	ST	DCG
SymPan - PANORAMA	0.785	0.544	0.673	0.778
PANORAMA	0.753	0.479	0.603	0.750
ROSy+	0.779	0.524	0.659	0.756
GSMD+SHD+R	0.731	0.472	0.602	0.721
DLA	0.713	0.429	0.552	0.687
DESIRE	0.658	0.404	0.513	0.663
LFD	0.642	0.375	0.484	0.642
SH-GEDT	0.553	0.310	0.414	0.584

(P-R) plots and five quantitative measures: Nearest Neighbor (NN), First Tier (FT), Second Tier (ST), E-measure (E) and Discounted Cumulative Gain (DCG) [SMKF04] for the classes of the corresponding datasets. For every query model that belongs to a class C , recall denotes the percentage of models of class C that are retrieved and precision denotes the proportion of retrieved models that belong to class C over the total number of retrieved models. The best score is 100% for both quantities. Nearest Neighbor (NN) indicates

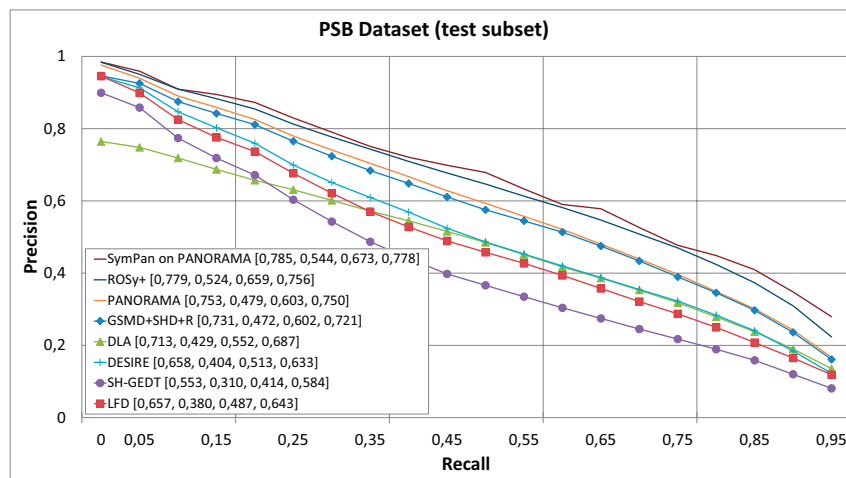


Figure 4: Precision-Recall plot for the Princeton Shape Benchmark test dataset. SymPan 3D model pose normalization method on PANORAMA retrieval results are compared against state-of-the-art 3D object retrieval techniques.

the percentage of queries where the closest match belongs to the query class. First Tier (FT) and Second Tier (ST) statistics, measure the recall value for the $(D - 1)$ and $2(D - 1)$ closest matches respectively, where D is the cardinality of the query's class. E-measure combines precision and recall metrics into a single number and the DCG statistic gives a sense of how well the overall retrieval would be viewed by a human [JK02]: similar shapes near the front of the list are more likely to appear at the top of the list.

In Fig. 4, using the experimental results given in [STP11], we illustrate the P-R scores for the test subset of the PSB dataset for the PANORAMA 3D object retrieval system, enhanced by the SymPan pose normalization method. Table 1 shows quantitative measures for the same methods. The results demonstrate that the proposed scheme outperforms state-of-the-art methods and significantly increases the performance of the PANORAMA 3D object retrieval system compared to its original pose normalization scheme.

In Fig. 5 comparative alignments between SymPan and CPCA, NPCA pose normalization methods on various 3D models from the PSB dataset, are illustrated. These alignments show that SymPan is able to produce accurate alignment results that, regardless of the originating class or the morphology of the input objects, are consistent and stable.

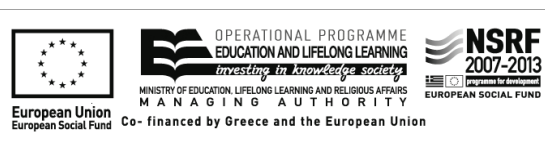
The proposed method was tested on a Core2Quad 2.5 GHz system, with 6 GB of RAM, running Matlab R2012a. The system was developed in a hybrid Matlab/C++/OpenGL architecture, which resulted in low computational times. The average pose normalization time for an 100,000 face 3D model is about 40 seconds.

5. Conclusions

A novel method for 3D model pose normalization based on a Normals' Deviation Map of the 3D model's surface as well as reflective object symmetry properties, is proposed. The proposed pose normalization method is based on information extracted from the 3D models by projecting them on their circumscribed cylinder. The quality of this alignment method is proven both visually and through the performance of a state-of-the-art 3D object retrieval system. Proper alignment is achieved regardless of the class or morphology of the 3D models.

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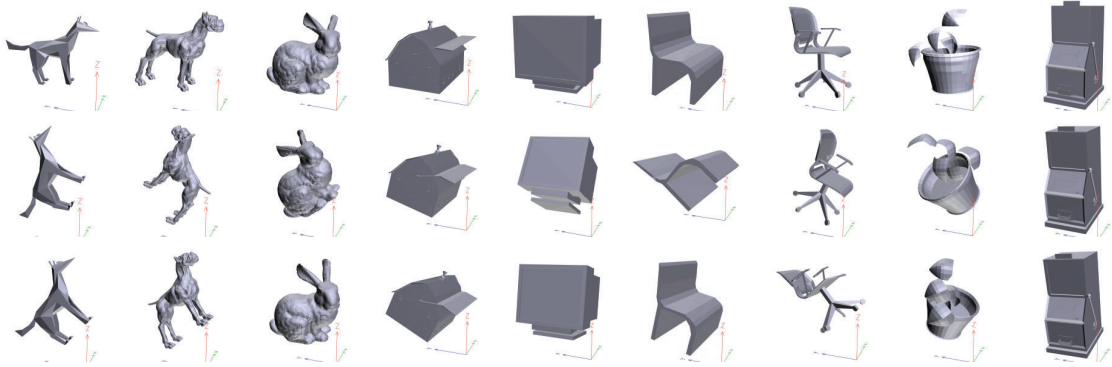


Figure 5: Sample alignments of 3D objects originating from different PSB classes. Top Row: SymPan alignment method, middle row: CPCA alignment method, bottom row: NPCA alignment method.