3D Alignment for Interactive Evolutionary Design

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Abstract. 3D model alignment ('Pose Normalization' in the literature) is investigated as part of wider research into guided evolutionary Computer-Aided Design. CAD technology in development will combine human interaction and geometric optimization, within an evolutionary design system. Evolving shapes will be influenced by simple pre-set geometric fuzzy-constraints – internal voids and external bounding geometry created by users. To compare evolving candidate shapes with these pre-set constraints they must first be aligned (rotated, scaled, and co-located). A shortlist of five promising alignment techniques is described. Benchmark data generated using standard CAD functions (centre of gravity, principle axes etc.) will be presented at the conference.

Keywords. Computer Aided Design, Pose Normalization, Interactive Evolutionary Computation, Geometric Evolutionary Optimization.

1. Introduction

Evolutionary Computation (EC) is often used for engineering and design problems that are too complex to tackle deterministically, and is generally focused on optimization and the later stages of design. EC is usually either automatic or interactive, with the latter well-suited for messy problems that are hard to model (e.g. the authors' primary area of interest of ideation within product design). Usable Interactive Evolutionary Computation (IEC) systems for design are emerging, but our research interests are distinct in focusing on Computer-Aided Design (CAD) methodologies to support early-stage concept generation by combining engineering optimization and IEC.

EvoShape (Figure 1) is a CAD application based on IEC, developed from original research into a Genetic Algorithm (GA) based system described in Graham et al [1]. It runs within a CAD environment, utilizing its geometric modeller and User Interface. Users guide the evolutionary process, from a random starting population of 3D shapes, purely through shape selection or rating.

The intention is to introduce more control to the users by allowing them to create simple guiding geometry at the start of the shape evolution process. This intention has resulted in the need to investigate 3D alignment techniques, the five most promising of which, shortlisted from a study of around 10, are analysed and compared in this paper.

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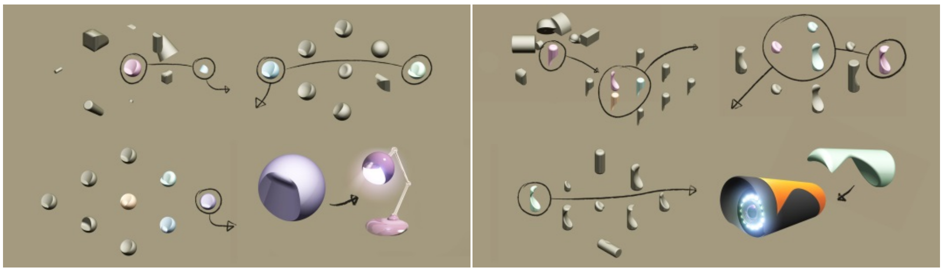

Figure 1. EvoShape.

2. Pose Normalization

The CAD application being developed by the authors requires users to create simple bounding geometry and internal voids, before they start to generate and explore 3D shapes. Bounding geometry may represent the overall proportions sought, and the voids could represent components within the products. To compare the evolving shapes with these soft-constraints, 3D form-comparison algorithms are being developed. But for these to work effectively, candidate and target shapes need to be aligned; this is commonly referred to in the literature as “Pose Normalization” (PN) [2,3,4,5,6].

2.1. Principal Component Analysis Methods

Farrugia et al [3] investigate various PN techniques for 3D vehicle models, concluding that there are two main techniques for rotational normalization:

- Principal Component Analysis (PCA) algorithm
- Computation of the symmetrical planes of a 3D model.

The symmetrical nature of vehicles should support the use of the symmetrical plane method but there is only one symmetrical plane on each vehicle. Farrugia et al [3] tested four different PCA methods on a downloaded database. These methods are:

- Principal Component Analysis (PCA)
- Centre of Gravity-PCA (CoG-PCA) [5]
- Normal-PCA (NPCA) [6] and
- Continuous-PCA (CPCA) [7]

The CoG-PCA method calculates the CoG of each mesh face rather than the actual vertices. In NPCA technique, the principal axes are identified by the covariance of the mesh face and not by the vertex points. The CPCA is the PCA method applied to an infinite continuous point set rather than a traditional discrete point set.

All these developments of the PCA differ from the original PCA only in the computation of the covariance matrix and they have been studied because many researchers have shown that the PCA technique may lead to inconsistent results.

Using the experimental results given by the authors, the CoG-PCA method was more effective regarding the computation time. The CPCA method had slightly better performance [8] than the CoG-PCA and noticeably better performance than the PCA and NPCA. Regarding reflection normalization, PCA was inadequate [9] while NPCA had inaccurate results in the three axes’ identification.

The CPCA-based PN method, in some cases can be un-successful in detecting some specific characteristics of 3D models such as symmetries, but they should be sufficiently effective when applied to IEC design systems.

2.2. Combined Pose Estimation (CPE)

Axenopoulos et al [4] combine plane reflection symmetry and recti linearity[2] to attain a 3D model alignment using the PCA method. Firstly, the 3D object is translated by locating the centre of the mass to the centre of the coordinate system, and then is scaled to fit within a bounding sphere. The object generates 2D views, and 2D rotation-invariant functionals are applied for each view. Rotation estimation takes place using a novel CPE method which combines the CPCA with plane symmetry and recti linearity.

If there are two or three planes of symmetry the transformation is kept as it is, otherwise the algorithm needs to be corrected using recti linearity. Recti linearity is invariant to scaling, translating and rotating. PCA and recti linearity are taking place at the same time and the one that produces the best rotation estimation is chosen.

After alignment, a set of 2D black/white views is extracted, and from each 2D view a descriptor vector is also extracted. These vectors are converted to a one-descriptor vector which describes the shape of the object. View-based similarity is computed by matching each 2D view between 3D models, so that the 3D models to be properly aligned in a coordinate frame.

The experimental results given by Axenopoulos et al [4] prove that CPE produce accurate rotation estimation results compared with the comparative techniques, and should achieve robustness in IED systems that use simple models. However, using the centre of the mass for translation normalization will not produce consistent alignment in more complex objects, as analysed in a later section.

2.3. Reflective Symmetry

A reflective symmetry computed on panoramic[3] views is used for a novel pose normalization method, as described by Sfikas et al. [10]. The symmetry plane of a 3D model is detected and the first axis of the model is computed. The other principal axes are computed by calculating the variance of the panoramic views. First, on a chosen cylinder the surface of the model is projected and aligned with a principal axis in space. A panoramic view representation is created by unfolding the 3D model over a 2D image plane. The 3D model's plane of symmetry is defined by the axis of the projection cylinder and the axis of maximum reflective symmetry. The 3D model's centroid is used to achieve translation normalization, and scale normalization is followed so that the 3D model exactly fits inside the unit sphere. A rotation of the symmetry plane takes place by orientating the surface so that it includes the Z axis, and the plane of symmetry is detected in the panoramic image where the symmetry score graph is extracted, as shown in Figure 2.

[2] The maximum ratio of the surface area to the sum of three orthogonal projected areas of the mesh.

[3] A panoramic view is a wide-angle view in a three-dimensional model.

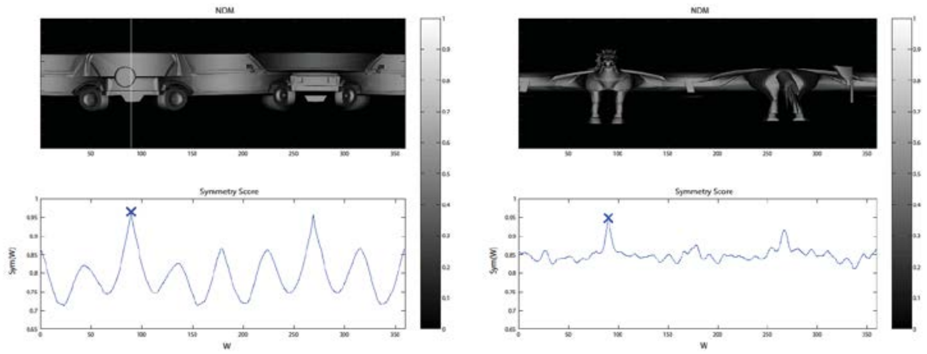

Figure 2. Panoramic images representing symmetric planes and associated symmetry score graphs [10].

Experimental results show that this method is accurate and with good performance but cannot handle complex 3D objects because symmetry detection either focuses on small fragments or bigger abstract areas of the 3D objects. In IEC design systems that use simple 3D models the reflective symmetry algorithm should achieve robustness. But systems with more complex models could produce inefficient alignments when using this method.

2.4. Non-rigid Shapes

Papadakis [2] describes the use of One-Class Support Vector Machines (OCSVM) to increase the consistency of translation and scale normalization under non-rigid shapes.

In translation normalization, the centre of mass of a 3D model is usually computed and located to the coordinates' origin. However, this technique is not effective in 3D objects that are articulated or have extruding parts and outliers (Figure 3).

To alleviate this problem, Papadakis [2] considers the surface of a 3D object as a collection of 3D points and use OCSVM to compute the decision surface and find the volume constrained within the boundaries of the decision surface. The centre of the object is the centroid of the distribution of the volume. The algorithm is identifying parts that are extremely small regarding the whole shape and that could derive negative results during the computation of the translation and scale.

In scale normalization, fitting a 3D model with these characteristics inside a unit cube is not effective due to the possible presence of outlying parts (Figure 3).

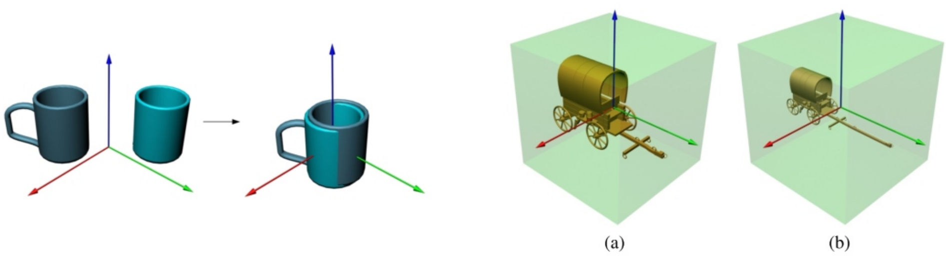

Figure 3. Left: Translation normalization using the centroid of the surface of the object, example in an object with and without extruding parts. Right: Scale normalization to the unit cube [2].

To normalize the scale, they calculate the average distance of the distribution of the object from its centre and scale the object in order this distance to be unit.

In the presence of non-rigid transformations, a method similar to the one described by Sfikas et al. [10], that depends on the symmetrical properties of the objects, becomes less descriptive. Many state-of-the-art approaches cannot accommodate 3D objects with articulations or extrusions, because the assumption that the centre of a 3D object is the centre of mass of the surface is not robust. The OCSVM methodology alleviates this problem and can probably be applied to IEC design systems that handle complex 3D objects with extruding and outlying parts, performing more consistent translation and scale normalization.

2.5. Planar-Reflective Symmetry Transform

Podolak et al. [11] describe a planar reflective symmetry transform (PRST) for 3D models that captures a continuous measure of the reflectional symmetry of a shape respectfully to all potential planes. This transform is computed by a Monte Carlo sampling algorithm which is constant under transformations, and determines the centre of symmetry as well as the principal symmetry axes which are essential for aligning models in a canonical system.

As shown in Figure 4, the darkest point (which indicates the greatest symmetry) is the centre of the object, and the main lines are the main axes. Alignments are usually computed with PCA using the centre of mass as the origin and the principal axes as the orientation. However, the results are not always correct (Figure 4).

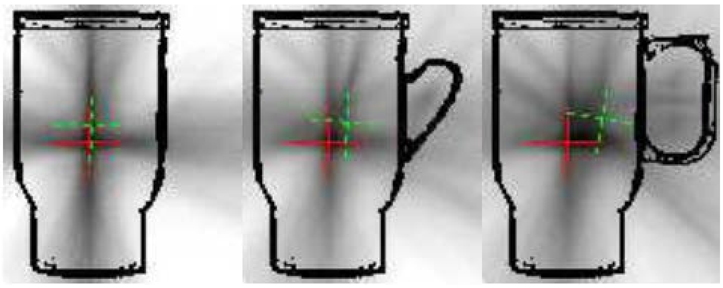

Figure 4. The PRST captures the degree of symmetry of arbitrary shapes with respect to reflection through all planes in space. The centre of mass and PCA axes are drawn in dotted green (they move depending on the presence of handles). The centre of symmetry and principal symmetry axes using PRST are shown in solid red (they remain constant under transformation of the shape) [11].

Podolak et al. [11] produce better alignments using PRST and introducing the centre of symmetry (COS) as well as the principal symmetry axes (PSA). The plane with maximal symmetry is the first PSA, the maximal symmetry perpendicular to the first is the second PSA and the plane which is perpendicular to both first and second axis is the third PSA. Finally, the intersection of those three planes is the centre of symmetry. This algorithm should achieve efficient normalization when applied in IEC design systems as the centre of symmetry and principal symmetry axes remain constant under transformation of shapes.

3. Conclusions

The main driver for PN research is the need to search databases of CAD geometry (e.g. parts libraries). Conveniently, it is also applicable to shape-comparison applications in the IEC design system being developed. Here, PN is essential to align pre-set guiding geometry with evolving forms generated by the combination of GA and CAD modeller. Five suitable PN candidates for IEC design system research were presented and compared. Since the IEC design system generates quite abstract and complex 3D models, the PCA-based PN method is recommended. This should be combined with a robust method similar to OCSVM to find the best 'centre' of objects for translation.

3.1. Related and Future Work

Basic PN functionality has been achieved using the CAD functions available through an Application Programming Interface (centre of mass, minimized bounding box, and principle axes). It is likely that this approach is not sufficiently accurate for the application, hence the parallel research into more sophisticated PN techniques. The next step is to develop shape-comparison algorithms, which will be used to allocate objective functions to evolving shapes – these will be combined with user scores to direct the evolutionary process. The results of this work will be presented at the conference for interest, and for future benchmarking purposes.

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