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Enhanced pose normalization and matching of non-rigid objects based on support vector machine modelling

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ABSTRACT

The estimation of 3D surface correspondence constitutes a fundamental problem in shape matching and analysis applications. In the presence of non-rigid shape deformations, the ambiguity of surface correspondence increases together with the complexity of registration algorithms.

In this paper, we alleviate this problem by means of 3D pose normalization using One-Class Support Vector Machines (OCSVM). In detail, we show how OCSVM are employed in order to increase the consistency of translation and scale normalization under articulations, extrusions or the presence of outliers. To estimate the relative translation and scale of an object, we use the 3D distribution of points that is modelled by employing OCSVM to estimate the decision surface corresponding to the surface points of the object under a preset tolerance to outliers. By discarding the outliers in the estimation of the object's center and size we compute the canonical pose of the core distribution that is less sensitive to intra-class shape variations. The effectiveness of the proposed method is demonstrated through the increased stability of translation and scale normalization and further justified by improving the precision of content-based 3D object retrieval.

1. Introduction

The increasing availability of 3D content together with the advent of affordable 3D acquisition technology has stimulated research in methods that facilitate the subsequent processing of 3D objects. Within the plurality of applications where 3D objects are used, one of the most commonly encountered problems is pose normalization which decomposes into the normalization of the translation, scale and rotation. Pose normalization is most often performed in applications such as content-based retrieval, thumbnail generation, visualization and modelling where 3D objects need to be positioned in a canonical frame. Pairwise surface registration provides the optimal solution for the shape correspondence problem that is drawing an increasing research interest and has recently been introduced in SHREC (SHape REtrieval Contest) [1,2]. Pose normalization is an alternative approach that provides a single, global solution for each 3D object instance which results in significant efficiency gains at the cost of sub-optimal surface correspondence.

In this paper, we focus on the translation and scale normalization components of the 3D pose normalization problem that have been relatively undervalued in comparison to rotation normalization. However, all three components are equally important to obtain consistent shape correspondence. We demonstrate that the state-of-the-art approaches for translation and scale normalization become insufficient as class-variation increases due to non-rigid shape deformations such as articulation, extrusion or the presence of isolated-outlying parts. To alleviate this problem, we propose the usage of a *novelty detection* algorithm, namely, the One-Class Support Vector Machines (OCSVM) [3,4] as a more robust approach. Using OCSVM we estimate the support of the high-dimensional distribution corresponding to a set of points sampled from the surface of a 3D object and derive the underlying distribution corresponding to the object as the 3D volume that is constrained within the boundaries of the OCSVM decision surface in 3D space. This distribution is then used to derive the relative translation and scale of the object in order to perform a more consistent normalization. This is achieved by lowering the sensitivity of normalization to relatively trivial parts of the object through outlier identification and employing a volume-based approach that is more descriptive compared to solely considering the surface of the object. A significant advantage of the proposed approach is its applicability to *polygon soup* 3D objects in contrast to state-of-the-art methods whose application is constrained to watertight 3D objects [2]. To evaluate the performance, we use a dataset of 3D objects where we introduce various extrusions, articulations or outliers and demonstrate the increased

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consistency of intra-class surface correspondence. We complement our experiments by demonstrating the performance gain that is achieved in content-based 3D object retrieval after employing the improved pose normalization process.

This paper complements and extends previous work presented in [5] mainly in the following aspects: (i) a thorough elaboration is provided in support of the formulation of the optimization problem, choice of the kernel, the setting of the parameters and implementation details, (ii) additional qualitative examples are provided from training to evaluation and (iii) the proposed approach is effectively employed to improve the performance of non-rigid 3D shape retrieval in several standard benchmarks.

The remainder of the paper is organized as follows: In Section 2, we discuss related work in the area of translation and scale normalization and outline the limitations of the state-of-the-art approaches in order to motivate the proposed methodology. In Section 3, we formally describe the context in which we employ OCSVM to estimate the distribution of a 3D object that is used to derive the corresponding normalizing translation and scale. In Section 4, we provide a quantitative evaluation that demonstrates the superiority of the proposed method in increasing the consistency of surface correspondence and in turn the performance of content-based retrieval, and finally, in Section 5, we summarize the contributions of this paper.

2. Related work

3D pose normalization accounts for the normalization of the translation, scale and rotation of 3D objects. This step is required in applications where 3D objects need to be positioned in a canonical coordinate frame as, in general, these three characteristics are arbitrarily set. For example, it is necessary in content-based retrieval when shape matching is based on the establishment of correspondences between the surfaces of objects and achieving invariance to isometric or non-isometric transformations.

In the domain of shape matching, the problem of achieving invariance to shape transformations may be viewed from three alternative perspectives. One family of methods concerns the extraction of transformation invariant shape features. As an indicative reference to related work, we may point to the '*Shape-DNA*' signature [6] as well as variants of diffusion and heat kernel descriptors such as those described in [7–10] that have become very popular due to their inherent invariance properties and discriminative power. Another family of methods address the problem of shape matching through pair-wise surface correspondence mainly on the basis of the well known ICP algorithm, that is often adjusted to provide more robust solutions according to the context, e.g. as in [11,12] or [13].

The last family of methods regards the normalization of the 3D pose of objects, in terms of similarity transformations. Among the three normalization problems, it is generally admitted that rotation normalization is the most challenging problem with a significant amount of related work [14–18], where the spatial, orientation or symmetry distribution of the surface has been used to determine the rotation of the frame of the object. However, since rotation normalization is performed on the basis of an appropriately chosen center of an object, translation normalization determines the effectiveness of pose normalization to a greater extent. Therefore, we focus on the translation normalization of 3D objects as well as scale normalization that has been relatively undervalued although it is a difficult problem in a number of cases.

Translation normalization. This problem is most frequently addressed by computing the center of mass of a 3D object and by translating it to make its center coincide with the coordinates origin. For 3D geometric objects consisting of polygons, the center

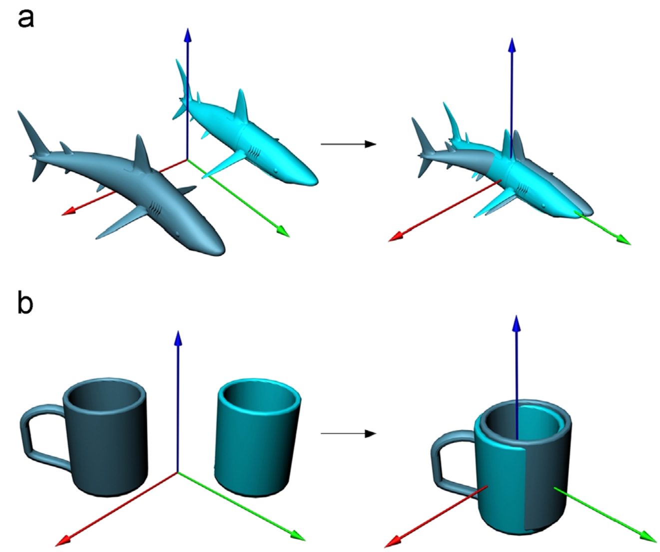

Fig. 1. Translation normalization using the centroid of the surface of the object; (a) example in an object with and without a non-rigid deformation and (b) in an object with and without extruding parts.

of the object is computed as a weighted average of the total set of the polygon vertices [19], or centroids of the polygons [14], i.e. as the centroid of its surface. For the majority of 3D objects, this method is effective and objects are well normalized with respect to translation. However, there are cases where this method is not appropriate such as articulated 3D objects or objects with isolated-outlying or extruding parts. Such cases are demonstrated in Fig. 1 (a) and (b), respectively.

Intuitively, we would agree that the centers of the two objects in either case should coincide (in a semantic context). However, by setting the centroid of the surface of an object as its center, we obtain a result that does not agree with our perception. As it is evident from the examples, a small change in the shape of 3D objects can have significant impact on the resulting translation normalization which may in turn negatively affect scale and rotation normalization. Clearly, we expect that the perturbation of the centroid of the surface of an object becomes more pronounced as the amount of articulation or extrusion increases.

In the work of Podolak et al. [16], the authors propose the center of symmetry computed by the Planar Reflective Symmetry Transform as an alternative approach to compute the center of an object. They show that this method is more robust in consistently determining the center of 3D scans of objects, however the performance of the method depends on the symmetry properties of the objects that become less descriptive in the presence of non-rigid transformations.

The smallest enclosing ball of an object [20] has also been considered as a method to determine its center as well as its scale [21]. However, this approach is directly dependent to the outlying parts of an object which makes it the most unstable method as will be demonstrated at Section 4.

Liu and Ramani [18] identified the negative effect of outliers in the rotation normalization component of pose normalization and employed a Random Sample Consensus (RANSAC) [22] approach to find the best model of the object's principal directions. However they did not investigate the effect of outliers in the estimation of the relative translation or scale, that together have a greater impact on the consistency of pose normalization.

Scale normalization. This problem is traditionally addressed by setting the scale of a 3D object to fit within a bounding volume of fixed size (unit cube or unit sphere), or to a size proportional to the