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Registration of partially overlapping surfaces by rejection of false point correspondences

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Abstract

We present a new algorithm for the registration of three-dimensional partially overlapping surfaces. It is based on an efficient scheme for the rejection of false point correspondences (correspondence outliers) and does not require initial pose estimation or feature extraction. An initial list of corresponding points is first derived using the regional properties of vertices on both surfaces. From these point correspondences, pairs of corresponding rigid triplets are formed. The normal vectors at the vertices of each corresponding triplet are used to compute the candidate rotations. By clustering the candidate rotation axes and candidate rotation angles separately, a large number of false correspondences are eliminated and an approximate rotation is decided, from which an approximate translation is also obtained. Finally, the optimal transformation parameters are determined by further refining the estimated parameters in an iterative manner. Mathematical analysis and experimental results show that the registration process is fast and accurate even when the objects are regularly shaped and contain many regionally similar surface patches.

Keywords: 3D registration; Overlapping surface; Triplet; Outlier rejection; Clustering; Iterative refinement

1. Introduction

The fast and accurate registration of two object surfaces in three dimensions is an important topic of research in computer vision and pattern recognition. The complexity of the problem is exacerbated if the two surfaces are only partially overlapping. An example of such an application is found in orthodontics. Given the scanned 3D image of a dental plaster model, one method of estimating the size and position of a (hidden) tooth root is to match a complete tooth of the same type (canine, incisor, etc.) with the visible crown.

Many methods have been proposed for 3D surface registration. They can be classified into feature-based algorithms, exhaustive-search algorithms, and algorithms that are based on the free-form surface representation. In the feature-based approaches, point features [1], curves [2], or regions [3] are used to find the correspondences. The advantage is that an initial estimate of the transformation parameters is not required, while the drawback is that the algorithms will fail when the 3D point data set contains very few salient local features. In addition, since the final result depends on the accuracy of the feature extraction algorithm, registration is likely to be biased when the local features are affected by noise.

The exhaustive-search algorithms rely on checking all possible alignments of two 3D data sets and counting the votes for each of these transformations. Among these, pose clustering [4,5] quantizes the space of candidate

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transformations and uses it as an accumulator in which each match increments a corresponding cell. In geometric hashing [6,7], a hash table is constructed and used to vote for the candidate corresponding k-tuples. While his method is still based on the hash table strategy, Mokhtarian [8] uses several curvature values in selecting feature points. Chen et al. proposed the RANSAC-based DARCES [9], in which every three control points are used to calculate a candidate transformation, and the final solution is obtained by verifying all those candidates. These exhaustive-search algorithms do not necessarily require feature extraction, and since they use a large number of points on the object surfaces, they are robust, especially in the partially overlapping case. However, the problem of combinatorial explosion will occur when the number of surface vertices is huge. Mesh simplification [10,11] offers a possible solution, but the mesh decimation process itself is time consuming and will result in the loss of surface detail.

Among the algorithms that are based on free-form surface representation, the iterative closest point (ICP) algorithm [12,13] has attracted much attention. Some improvements have been made to it over the years [14,15]. However, the drawbacks of this approach are that (a) it requires a good initial estimation of the transformation parameters, (b) the computational cost in searching for the nearest point is high when the number of vertices on the two surfaces is large, and (c) it is difficult to determine the extent of overlap between the two surfaces.

Other methods based on free-form surface representation solve the registration problem by extracting the free-form surface properties, e.g. the spin image proposed by Johnson et al. [16–18]. Other algorithms of this kind include spherical representation [19], COSMOS [20], point signature [21], surface signature [22], 3D point's fingerprint [23], harmonic shape image [24] and symbolic surface signature [25]. These methods do not rely on prior estimation of the transformation parameters, and some of them can handle relatively featureless surface patches. However, there is the possibility that the 3D surface data are corrupted by noise, which results in some false point matches. In addition, when faced with smooth-surface objects that contain many regionally similar surface patches, the problem of multiple correspondences inevitably occurs. These correspondences also include false ones that must be rejected in order to obtain a correct transformation.

To reject the false point correspondences, a general approach is to group each pair of corresponding points based on their ability to help form a consistent hypothesis. Some common consistency tests are the distance constraint, angle constraint and orientation constraint [26]. These metrics lead to the formulation of the hypothesize, test and alignment paradigms [2,27], where the minimal number of correspondences required for the registration are proposed and then verified. Johnson et al. [16] also suggested that geometric consistency be used to filter out correspondence outliers in a robust manner, in which the geometric consistency measure D_{gc} of correspondences $C_1 = \{s_1, m_1\}$ and $C_2 = \{s_2, m_2\}$ is defined as

$$D_{gc} = \max(d_{gc}(C_1, C_2), d_{gc}(C_2, C_1)),$$

$$d_{gc}(C_1, C_2) = 2\,\frac{\|S_{m_2}(m_1) - S_{s_2}(s_1)\|}{\|S_{m_2}(m_1)\| + \|S_{s_2}(s_1)\|},$$

where $S_{m_2}(m_1)$ is the spin-map that describes the regional distribution of surface vertices. If the geometric consistency measure D_{gc} is small, the two correspondences are considered geometrically consistent. The geometric consistency measure of every two correspondences are calculated and compared with all the others. Only when one pair of corresponding points is geometrically consistent with at least one quarter of all the correspondences, can it be regarded as correct.

All these strategies to reject correspondence outliers have the advantages of robustness and ease of implementation. However, they require the comparison between each pair of corresponding points, which means a computational complexity of $O(n^2)$ if there are n pairs of candidate point correspondences. When the objects have many regionally similar surface patches, there will be a large number of multiple correspondences and hence a heavy computational burden.

Rodrigues et al. [28] have also employed the idea of essential point to reject false correspondences. For every candidate point correspondence, the two relative gaps of each reflected correspondence is computed. If any of these two gaps deviates too much from its mean value, this candidate correspondence is regarded as a false one and eliminated. This method does not require the comparison between every two candidate correspondences, but is only used as an improvement to the traditional ICP. Moreover, this method assumes that the rotation angle is less than 180°.

None of the 3D surface registration algorithms discussed above is suitable for our application for the following reasons:

(a) Since we have no prior knowledge of the approximate transformation between the two surfaces to be registered, an initial estimate of the transformation parameters cannot be given if the ICP algorithm is to be used.
(b) Since the objects that we mainly consider (e.g., tooth crowns) have generally smooth surfaces with relatively few salient features, feature-based methods are not appropriate.
(c) Given the large number of mesh vertices, a combinatorial explosion is likely if the two surfaces are registered by checking all possible transformations. Therefore, the registration process will not be efficient if an exhaustive-search algorithm is adopted.
(d) The 3D objects usually contain many regionally similar surface patches, which means there may initially be many false point correspondences when the comparison is based on the free-form surface representation of 3D