Image and Vision Computing 28 (2010) 563–570

Contents lists available at ScienceDirect

Image and Vision Computing

journal homepage: www.elsevier.com/locate/imavis

A high-accuracy method for fine registration of overlapping point clouds

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ARTICLE INFO

Article history:
Received 17 June 2008
Received in revised form 31 August 2009
Accepted 17 September 2009

Keywords:
Fine registration
ICP algorithm
Dual interpolating point-to-surface
Surface fitting
Auxiliary pair

ABSTRACT

This paper presents a high-accuracy method for fine registration of two partially overlapping point clouds that have been coarsely registered. The proposed algorithm, which is named dual interpolating point-to-surface method, is principally a modified variant of point-to-surface Iterative Closest Point (ICP) algorithm. The original correspondences are established by adopting a dual surface fitting approach using B-spline interpolation. A novel auxiliary pair constraint based on the surface fitting approach, together with surface curvature information, is employed to remove unreliable point matches. The combined constraint directly utilizes global rigid motion consistency in conjunction with local geometric invariant to reject false correspondences precisely and efficiently. The experimental results involving a number of realistic point clouds demonstrate that the new method can obtain accurate and robust fine registration for pairwise 3D point clouds. This method addresses highest accuracy alignment with less focus on recovery from poor coarse registrations.

1. Introduction

Reverse engineering is being widely used in modern manufacture. It is well known that laser scanners can obtain large amounts of 3D coordinates which are usually called point clouds in a short period of time in reverse engineering. However, due to occlusions and limited field of view of the laser scanner, the complete 3D acquisition of a given object is difficult even impossible, therefore in many cases the object has to be scanned from different viewpoints in order to completely reconstruct it. Because these sectional point clouds are acquired from different positions and each point cloud has its own local coordinate system, all of them must be transformed into a common coordinate system by determining the Euclidean motion between different views. This procedure is usually referred to as registration. High-accuracy registration is a crucial step in 3D modeling in reverse engineering to acquire accurate data body as well as to eliminate systematic errors caused by misalignment.

The registration process for two point clouds is to determine the best geometric transformation that brings one cloud into alignment with the other in a common coordinate system. At present, according to a recent study of the state-of-art concerning surface registration techniques [1], all the existing methods of registration can be divided into two main groups: coarse registration and fine registration. In coarse registration, the purpose is to compute a rough estimation of the rigid motion between two point clouds. In general, some Euclidean invariants and geometric features [2,3] are adopted with the aim of establishing a set of correspondences used to compute an initial motion between the two datasets. Some researchers solve this problem by using a mechanical device, such as a turntable [4,5], to achieve the geometry motion between them. In some applications, markers or other references are added to the object or to the measuring scenario [6] in order to establish the rigid transformation from these references. Generally, the result of coarse registration is poor, therefore a fine registration technique is necessary to improve data merging accuracy.

In fine registration, the aim is to obtain a more accurate solution of the Euclidean motion bridging the two point clouds by iteratively minimizing the distance between the two surfaces. These methods for fine registration refine the transformation matrix by minimizing the distances between temporal corresponding points on both surfaces. The best-known method for fine registration of 3D point clouds is the Iterative Closest Point (ICP) algorithm [7]. Actually ICP and its variations have become the dominant methods in the registration literature. ICP can be divided into two steps: the first is to determine correspondences between different datasets representing the same free-form surface obtained from different viewpoints, the second is to estimate the transformation parameters bringing one dataset into alignment with the other. The two steps are iterated until the estimated motion parameters come to convergence.

Generally, according to the existing methods for finding correspondences between different datasets, the ICP algorithms and its variations can be classified into three approaches: point-to-point, point-to-projection and point-to-surface. The traditional Iterative Closest Point algorithm proposed by Besl and McKay [7]

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doi:10.1016/j.imavis.2009.09.006

is a point-to-point approach and it is one of the most common techniques for fine registration of partial 3D surfaces. Correspondences are established by searching for the points in the destination dataset that are closest to a set of points in the source dataset, and then point to point distances are minimized to determine the transformation parameters. Although this method is easy for operation, an appropriate initial value for optimal operation is desired to avoid a local minimum result. Besides, the nearest pairs are not necessarily the reasonable corresponding pairs and thus lots of false correspondences are introduced by using this criterion, and this greatly limits the performance of the point-to-point method.

The point-to-projection approach finds the correspondence of a source point by projecting the source point onto the destination surface from the point of view of the destination surface [8,9]. Since time-consuming search is avoided, the approach is fast, however, the registration accuracy is not so satisfactory [10].

The point-to-surface approach is known to be the most accurate [10] and is widely used due to its precision and robustness. The objective of point-to-surface algorithm is to estimate the relative transformation parameters that minimize the sum of the square of the distances between points and their corresponding surfaces. The most widely used point-to-surface approach is the point-to-plane proposed by Chen and Medioni [11]. They minimize the distances from points in the source dataset to tangential planes at corresponding points in the destination dataset, instead of point-to-nearest-point distance. Other point-to-surface approaches such as point-to-NURBS [12] and point-to-B-spline [13] are also proposed to solve the fine registration problem. Although finding the intersection on the destination surface is computationally expensive, the point-to-surface approach converges in less iterations and is less likely to be influenced by local minima so that higher accuracy and efficiency can be guaranteed compared with the point-to-point and point-to-projection method [10]. Park and Subbarao [14] introduce an efficient point-to-plane registration technique by combining the high-speed advantage of point-to-projection technique. In the algorithm, the source point is forward-projected to the destination surface, and the projection point is reprojected to the normal vector of the source point in order to find the corresponding point fast and accurately.

From another point of view, the method of establishing constraints to remove unreliable correspondences accurately is essential in fine registration. Actually, due to the limitation of the ICP algorithms when establishing corresponding points, none of these found correspondences are absolutely "true" matches, and false pairs can always generate negative influence on the convergence of the ICP to a correct solution. Therefore many matching constraints are proposed with the aim of rejecting unlikely correspondences. The Iterative Closest Compatible Point (ICCP) algorithm [15,16] reduces the search space of ICP by using invariant attributes. In the algorithm, the distance minimization is performed only between the point pairs considered compatible on the basis of their viewpoint invariant attributes such as curvature and angle between normals (for example, allowing points to match only if their associated normal vectors differ by less than 45°). Chua and Jarvis [17] use principal curvature and direction constraint to remove false pairs. An approach called Iterative Closest Points using Invariant Features (ICPIF) proposed by Sharp et al. [18] use shape features in conjunction with point positions for fine registration. The weighted invariant features, including principal curvatures, moment invariants and spherical harmonics invariants, together with the positional information, are combined to construct a weighted feature distance function for choosing the corresponding points. Kase et al. [19] employ the Extended Gaussian Curvature to calculate the difference between possible corresponding points for the local evaluation. The principal curvatures are used and a matching rate function is designed to evaluate the local errors. In a modified ICP algorithm proposed by Guehing [20], the corresponding points are defined as the point pair that is sufficiently close in both of distance and normal directions. A pair of points is considered to be compatible only if their distance is not too far away and their normal directions are not deviated too much.

The Iterative Closest Reciprocal Point (ICRP) algorithm [21] makes the matching symmetric by back-projecting a found corresponding point in the destination surface onto the source surface. Dorai et al. [22] propose a distance constraint imposed by rigid transformations. In the algorithm, a pair of corresponding points is considered to be reasonable if and only if they are consistent with other corresponding pairs. Zinsser et al. [23] propose a robust method known as the Picky ICP algorithm in which a threshold is fixed at a given multiple of the standard deviation, and only corresponding pairs with the smallest distances are used in the motion computation at every iteration step. Liu [24] combines the collinearity constraint and closeness constraint to reject false matches based on the possible point matches established by the traditional Iterative Closest Point criterion.

In summary, the geometric properties and transformation invariants are most widely used in removing false matches when fine registration is demanded. Actually, different constraints correspond to different requirements such as accuracy, speed and applicability of the measurement system. Different constraints are usually combined to make the resulting ICP variants efficient and accurate. However, although ICP and its modified variants are the most common registration methods because of their good performance with respect to implementation, applicability and computational efficiency, there are also some inherent drawbacks to be solved, such as the problems of convergence to a local minimum, the requirement for lots of iterations and the unsatisfactory surface quality in the overlapping region after registration.

In this paper, a modified ICP variant is presented in order to improve the accuracy and robustness of ICP for free-form surface registration. We assume that the coarse registration has been done and concentrate on the fine registration phase. In addition, we focus only on aligning pairwise point clouds and do not address the global registration problem [25,26]. We propose an accurate variant of the point-to-surface registration technique based on dual surface interpolation approach, which is called dual interpolating point-to-surface method. In order to establish corresponding points accurately, we propose the auxiliary pair constraint and combine it with curvature constraint to reject false correspondences. The combined constraint utilizes the global rigid motion consistency and local geometrical invariant to produce accurate matching results. The experiment results demonstrate the validity and accuracy of the proposed algorithm.

The following of the paper is organized as: first, a brief overview of our registration algorithm is presented in Section 2. Then, Section 3 presents our proposal in detail including surface reconstruction, correspondences establishment and transformation parameters estimation. Experimental results using real datasets are presented in Section 4. The article ends with conclusions.

2. Overview of the method

In this section, an overview of the proposed method is provided after a brief description of the procedure of ICP algorithm. Suppose two corresponding datasets $\mathbf{P}$ (on the source surface) and $\mathbf{Q}$ (on the destination surface) are established using a certain matching criterion, and the number of the corresponding pairs is n. The registration task is to estimate a rigid transformation $\mathbf{T}$ which is composed of rotation matrix $\mathbf{R}$ and translation vector $\mathbf{t}$ to minimize an objective function: