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Nonrigid iterative closest points for registration of 3D biomedical surfaces

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ABSTRACT

Advanced 3D optical and laser scanners bring new challenges to computer graphics. We present a novel nonrigid surface registration algorithm based on Iterative Closest Point (ICP) method with multiple correspondences. Our method, called the Nonrigid Iterative Closest Points (NICPs), can be applied to surfaces of arbitrary topology. It does not impose any restrictions on the deformation, e.g. rigidity or articulation. Finally, it does not require parametrization of input meshes. Our method is based on an objective function that combines distance and regularization terms. Unlike the standard ICP, the distance term is determined based on multiple two-way correspondences rather than single one-way correspondences between surfaces. A Laplacian-based regularization term is proposed to take full advantage of multiple two-way correspondences. This term regularizes the surface movement by enforcing vertices to move coherently with their 1-ring neighbors. The proposed method achieves good performances when no global pose differences or significant amount of bending exists in the models, for example, families of similar shapes, like human femur and vertebrae models.

1. Introduction

The proliferation of optical and laser scanners leads to a variety of applications such as computer-aided design, virtual reality and medical diagnosis and treatment [1]. The goal of surface registration is to find a transformation which best superposes one surface with another [2]. Typically, this is done by transforming the *source surface* to make it as close as possible to the *target surface*. There are two variants of the registration problem: rigid and nonrigid. In rigid registration, the transformation that is applied to the source surface is required to be an orientation-preserving isometry (superposition of a rotation and a translation). In nonrigid registration, one is allowed to deform the source surface to improve the solution.

This paper addresses the nonrigid registration problem, which has numerous applications in medical imaging, computer graphics and computer vision. Non-rigid registration algorithms can provide correspondence information for two similar shapes by deforming one to another. The correspondence information can be used in

- example-based segmentation [3];
- interpolating [3] or animating [4] models;
- computing low-dimensional representations of shape families, such as PCA models [5–7];
- comparing different shapes in a same family (for example, analyzing the growth of an organ over time) [8,9].

Our registration algorithm follows the Non-rigid ICP framework introduced in [10]. The difference is that we search for multiple two-way correspondences rather than single one-way correspondences between the source and the target. The algorithm is built around an energy minimization process similar to [11], where the energy contains a distance term and a potential energy term. Potential energy terms of [10] or [12] can be used with our multiple two-way correspondences. However, a slightly modified potential energy term allows the surface to deform more freely. This distance terms of existing methods [8–13] can also be used with multiple two-way correspondences.

1.1. Contribution

This paper focuses on automatically non-rigidly registering human bone shapes and further building the statistical shape models fully automatically, providing the basis for distortion organ registration, intropatient registration and altas registration, which are crucial to disease

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analysis and treatment planning. In the field of Biomechanics, the registration step is always performed by human and is labor intensive. The registration process for each pair of human vertebrae models shown in our paper often takes 3 h for a Biomechanics graduate student. In addition, the manual registration may also be subjective. To alleviate these problems, we develop a fully automatic method to help biomechanics researchers. The main contributions of this paper are

1. a multiple two-way correspondence search scheme,
2. a Laplacian-based potential energy, and
3. giving a way of registering similar shapes without any prior assumptions on underlying deformations, such as rigid, isometric. This registration achieves the requirements of biomechanics researchers, in addition, does not bring any subjective bias about what the deformation should be. Therefore, the method is suitable for any biomedical surface registration and the following statistical shape analysis.

Most of the existing registration methods rely on single correspondence, i.e. they assign a single point on the target surface to a point on the source surface. However, this is inadequate in many cases. For example, when there exist false single correspondences, the registration may be trapped at local minima. When the source and the target are relatively *far* away, multiple correspondences in both directions (source to target and target to source) can be used to facilitate the registration. This scheme serves as a heuristic for pulling the registration process out from local optima. Local geometric information (in our case, normals) is used to remove incorrect correspondences. This improves the robustness of our approach while keeping the objective function simple. A Laplacian-based potential energy is also proposed. This regularization term works better than others when incorporated with the new correspondence search scheme.

The multiple two-way correspondence search scheme is similar to coarse-to-fine correspondence search presented in [9] or [14]. In these papers, coarse alignment is firstly performed on some pre-computed features of a mesh, and then propagated to other places via diffusion [9] or local weighted combinations [14]. However, because of measurement errors and natural variability of shapes, extracted feature points may not be accurate and may not be in one-to-one correspondence. More comprehensive review of the related work, including other methods based on multiple correspondences, can be found in Section 2.

2. Related work

In this section, we briefly review the existing surface registration schemes, focusing on those based on the nonrigid ICP method. More complete review of recent results on surface registration can be found in survey paper [15].

2.1. Surface registration

In rigid registration, the space of transformations is low-dimensional. However, in nonrigid registration, the amount of allowed shape deformations is model-dependent and high dimensional [16]. When there is small distortion between the source and the target, the nearest neighbor correspondence is adopted as an initial guess. The deformation is controlled by a regularized version of this correspondence field. Andresen et al. apply an explicit convolution to the nearest neighbor displacements [8,9] to form the initial correspondences in each iteration of the registration. In [14,17], thin-plate splines are used to regularize the point movement. In [12], an implicit regularization term based on Laplacian coordinates is proposed. While it preserves the shape well, it tends to strongly limit the deformation and therefore it is not suitable for our application. In [10], a locally affine regularized point motion is used along with the nearest neighbor correspondence criterion. Mitra et al. [18] present a space-time surface registration algorithm. The input to their algorithm is a large number of scans parametrized by time, rather than a pair of surfaces.

However, when the required deformation is larger, the above-mentioned methods often yield unsatisfactory results. The current strategy of dealing with larger deformation is to add restrictions on the deformation, or on the input surfaces.

Some methods impose restrictions on input surfaces. For example, many methods [19–22] rely on conformal mapping or spherical parameterizations, such as Möbius transform. The basic idea is to first map the surfaces to planar domains or spheres [23–25] and then solve the matching problem in the other domain, which is better studied. The input surfaces of these methods must have genus 0. Carrying over these techniques to higher genus surfaces would require cutting the source and target surfaces in a consistent manner, which by itself is a hard problem.

Some other methods impose restrictions on required deformations. For example, Chang and Zwicker's method [26–28] and Huang et al.'s method [3] perform well on modeling articulated motions between surfaces.

2.2. Nonrigid ICP

The classic registration method is the Iterated Closest Point (ICP) algorithm [29,30] (originally developed to solve the rigid registration problem). It works by iterating the following three steps:

1. Correspondence determination: Select points on the source surface (source points). Pair each source point with its closest point (target point) on the target surface.
2. Error minimization:Compute a rigid transformation T that minimizes the mean square error between the source points (transformed with T) and their corresponding target points.
3. Update: Apply transformation T to the source surface; stop if T is close to the identity transformation.

ICP is a local optimization algorithm, which generally requires close initialization (i.e. that the input source and target surfaces are close to being aligned) to converge. If initialization is close enough, the method is robust and usually converges monotonically.

Numerous improvements and extensions of the ICP algorithm have been proposed. Some of them focus on the correspondence determination stage. Examples include [17], based on fuzzy correspondences, Expectation Maximization based iterated closest point (EM-ICP) [31] and a method based on a priori knowledge [32]. By altering the error minimization step, one can develop nonrigid registration algorithms. The key is to change the optimization problem in a way that makes nonrigid transformations feasible, for example as described in [10,17,32]. In [33], a non-Euclidean distance which depends on a unit normal difference is used as the distance between two surfaces. This accelerates convergence, but makes the optimization problem non-quadratic, and thus increases the computational complexity.

2.3. Other multiple-correspondence-based schemes

Using multiple correspondences to avoid local minima is not a new idea [17,31,34–38]. The basic motivation of doing so is that matching single points is not as robust as matching clusters of points. Specifically, when there are some assumptions on motion of points, like rigidity [31,34] or articulated motion [4,26–28,39,40], matching patches or grouped points rather than single points is always the right way to go.

The main purpose of our method is to discover the variation space between a set of similar surface models with no a priori information (Section 6). Therefore, we cannot impose rigidity or articulation constraint on the deformation. Our method does not require the motion to be rigid or articulated and is designed to work with surfaces rather than feature point set. When methods that are designed for registering articulated shapes are applied to input surfaces we are interested in, the resulting deformation is typically of poor quality. For example, the registration result of one pair of the vertebrae obtained by Chang and