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Landmark transfer with minimal graph[☆], [☆☆]

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We present an efficient and robust algorithm for the landmark transfer on 3D meshes that are approximately isometric. Given one or more custom landmarks placed by the user on a source mesh, our method efficiently computes corresponding landmarks on a family of target meshes. The technique is useful when a user is interested in characterization and reuse of application-specific landmarks on meshes of similar shape (for example, meshes coming from the same class of objects). Consequently, across a set of multiple meshes consistency is assured among landmarks, regardless of landmark geometric distinctiveness. The main advantage of our method over existing approaches is its low computation time. Differently from existing non-rigid registration techniques, our method detects and uses a minimum number of geometric features that are necessary to accurately locate the user-defined landmarks and avoids performing unnecessary full registration. In addition, unlike previous techniques that assume strict consistency with respect to geodesic distances, we adopt histograms of geodesic distance to define feature point coordinates, in order to handle the deviation of isometric deformation. This allows us to accurately locate the landmarks with only a small number of feature points in proximity, from which we build what we call a minimal graph. We demonstrate and evaluate the quality of transfer by our algorithm on a number of Tosca data sets.

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1. Introduction

Landmarks play a central role in many algorithms, including correspondence computation, and shape analysis, which deal with highly relevant problems in shape retrieval. Consequently, a lot of attention has been paid to landmark extraction and matching problems during the past decade. While most existing landmark extraction methods use geometrical prominence as a main criterion of feature selection, landmarks can often be defined from the semantics that are specific to applications, independently from geometric saliency. This is particularly true for anthropometric studies [1] or computer animation [2]. Moreover, landmarks are often not persistent across pose changes or inter-subject variations.

So far, when a user is interested in characterization and selection of points on a mesh without a strongly distinguishable geometric saliency, we have often relied on manual labeling. Manual labeling has also been almost the only trustworthy way when the objective is to obtain a persistent set of landmarks across a set of multiple meshes. Existing techniques on automatic landmark extraction [3,4] and matching may not work well in such cases, since the geometric features are not necessarily persistent across deformations; for instance, in case of non-rigid deformations.

However, the work spent on manually labeling and associating landmarks is tedious and time consuming. Thus, in this work we aim at developing techniques to help with the reuse of the landmarks defined by the user, so that consistency can be assured with a minimal user input, regardless of geometric distinctiveness of the landmarks.

Our landmark transfer technique allows the user to define one or more custom landmarks on a source mesh, and efficiently computes meaningful correspondences on a family of target meshes that are approximately isometric. We develop our method for uniquely describing any given point on the shape, which is not necessarily geometrically significant. A good advantage of our method in comparison with relevant/existing techniques is its fast computation time. This is possible because our method is optimally designed for transferring a sparse set of landmarks on multiple target models while avoiding unnecessary full registration.

With the goal of optimal landmark transfer towards obtaining a consistent set of landmarks across multiple sets, we make several smaller contributions:

(1) We develop the idea of the minimal graph (Section 5), which is used for landmark transfer with minimum computation.
(2) Identification of landmark points using a newly defined geodesic coordinates (Section 6.1): in contrast to previous approaches, we do not rely solely on geodesic distances. Instead we develop a reliable method of updating geodesic distances, which compensates well for distance changes due to imperfect isometry and assures precise and consistent landmark location.

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2. Related work

In some sense, the problem we are solving in our work can be seen as a sub-problem of full correspondence, although it should be noted that our technique is tailored for the fast transfer of a sparse set of user-defined landmarks. Thus, we give a brief review of recent techniques devoted to surface registration here. In most existing registration techniques, to make the problem tractable, a smaller number of sparse correspondences are preceded, before it can be extended to a full correspondence. This strategy is often adopted for both inter-subject deformations [5,6] and approximate/near isometries of the same object [7–9]. These landmarks, whether automatically sampled/extracted [7–9] or manually labeled [5,6], facilitate specifying the rough physical characteristics or poses, so that the matching is made easier especially when surfaces exhibit large deformations.

Methods handling the large deformation can be classified into two categories: those that deal with large deformations of the same object (inter-subject registration) and those that register large inter-subject deformations. Inter-subject registration often relies on isometry-invariant local descriptors to select geometric feature points; then finds a matching among them such that the pairwise geodesic distances between all feature point pairs are preserved. Chang and Zwicker [7] developed an algorithm that assumes skeleton driven deformation among the meshes. They use the spin image as a feature descriptor and measure similarity between descriptors to find matches on a subset of vertices. For each match they generate a rigid transformation and cluster the resulting set of candidate transformations to obtain the final set of transformations. Assigning the transformations to the shapes has been made by using graph cuts optimization. Non-rigid registration proposed by Huang and coworkers [8] can be seen as a variant of the ICP (iterative closest point) algorithm, it finds optimal matching among a subset of vertices by using the Euclidean and feature distances among matching pairs. Tevs and colleagues [9] presented a RANSAC-like matching algorithm. For a set of random source points, they select the corresponding target points according to a probability function that measures the accuracy of the matching. The matching is further extended by adding additional correspondence in a way that they do not violate the isometric matching criterion. Later, the authors have extended their idea [10] by proposing a planning step to find an optimal set of feature points, instead of choosing the source points randomly. These points are matched first so that matching process converges to the solution as quickly as possible. More recently, Ovsjanikov et al. [11] have shown how dense isometric maps can be found among nearly isometric surfaces from a single correspondence, by using the Heat Kernel Map (HKM).

Most intra-subject registration techniques in computer graphics have been devoted to matching among different scans of human bodies [5,6]. They assume manually labeled landmarks on the surface and cast the matching problem as an optimization one, by using the error terms: the sum of Euclidian distances among corresponding landmarks, surface distance, and distortions of the surface under deformation. Lipman and Funkhouser [12] use Möbius transformations defined by a set of three randomly sampled points on each of the two point sets, and produces correspondences via a voting algorithm. They have shown that the algorithm can automatically find dozens of point correspondences between different object types belonging to the same class in different poses. Kim et al [13] also adopted Möbius transformations on conformal maps of each mesh, which have been computed from subsets of previously found sparse correspondences among feature points to produce a number of maps. These maps are then blended with weights that are computed with an objective function that favors low-distortion everywhere.

While it is possible to eventually consider these methods for the landmark transfer problem, our setting is different from (sparse or dense) matching of isometric surfaces. First, we assume that a sparse set of landmarks is provided by the user. This allows the user to define application-specific landmarks, independently from the geometric saliency. Second, our method efficiently computes a coherent set of corresponding landmarks on a number of target models. Unlike most existing methods that focus on computing global optimal solution to the full correspondence, we perform the transfer in one-by-one basis while avoiding unnecessary and costly full registration.

Graph matching has been successfully adopted in shape matching [14] and symmetry detection [15]. In our work, we use graphs for assisting the matching of geometric feature points within and between meshes. Graphs are constructed using geometric feature points as nodes; edges between connected feature points are weighted by the geodesic distances between the two.

3. Overview

The different steps of our algorithm are illustrated in Fig. 1. First, we build a graph G_F on the source mesh M_S, whose nodes are the set of automatically selected geometric feature points and the edges are composed of geodesic paths between the nodes (Fig. 1(a)). Then, given a user-specified landmark, we build what we call the minimal graph G_M, a subgraph of G_F (Fig. 1(b)). The graph G_M has three main properties: (1) it uniquely defines the user-provided landmark, (2) it is as small as possible in terms of number of nodes and geodesic distances, (3) it is a unique subgraph of G_F, i.e. there is no other subgraph in G_F that matches with G_M.

Next, given a target mesh M_T, we select a set of points with the local shape signatures similar to the points from graph G_M. From these feature points we compute the graph $\widehat{G}_F$ by connecting the points which are within the maximum geodesic radius of G_M (Fig. 1(c)). Then we use the approximate graph matching technique to find $\widehat{G}_M$, a subgraph of $\widehat{G}_F$, that best matches with G_M.

Finally, now that we have G_M matched with $\widehat{G}_F$ on the target mesh, we can find the corresponding landmark location on the target mesh by using $\widehat{G}_M$ (Fig. 1(d)). This task would be made easier if the source and target meshes are perfectly isometric, since we can simply use the geodesic distances from each of the geometric feature points to be able to uniquely identify the landmark location. Unfortunately, the meshes are only approximately isometric and such a method may fail to estimate the landmark location reliably, especially when the deformation between the two meshes is large. We solve this problem by interpolating the updated geodesic distances on the target mesh in order to compensate changes in those that were induced due to non/roughly isometric deformation.

3.1. Assumptions

Like many existing non-rigid registration methods, we expect that the meshes are approximately/nearly isometric. Techniques developed with such an assumption are appreciated in many applications dealing with the matching of 3D scan data of deforming objects.

As is the case with many real-world applications, we assume that the landmarks are sparse and develop our algorithm that is optimally tailored for such cases. However, our method can be easily extended to complete matching, with the modification of the use of the minimal graph. We discuss this point in further detail in Section 8.

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