Topology-Adaptive Non-Rigid Registration for 3D Facial Scans

Yujian Gao, Shuai Li, Aimin Hao, and Qinping Zhao

Abstract—**3D scans are usually stored as range images or point clouds, which are inconvenient to be utilized in common graphics pipelines. Therefore non-rigid registration is required to convert the scans into triangulated 3D models. Traditional non-rigid registration methods deform and register a topology-stable template to approximate the point cloud without considering the complexity of the scanned object, this will lead to bad registration or redundancies in the results, especially for 3D dynamic, densely-sampled facial scans with a large number of degrees of freedom. To address this problem, in this paper we propose a new topology-adaptive non-rigid registration method for 3D facial scans. Our method avoids the drawback of traditional methods by combining the advantages of non-rigid registration and mesh subdivision/simplification. It reduces the redundancy of registered results effectively and guarantees the accuracy of registration by adding or removing triangles of template models. We introduce of the working principle of our method, then evaluate our technique with a variety of models, and finally give a quantitative analysis of the registration results.**

Index Terms—**Non-rigid, topology-adaptive, registration, facial scans.**

I. INTRODUCTION

As 3D scanning technologies continue to improve, 3D dynamic densely-sampled data is becoming more and more prevalent. Non-rigid registration of scanned model is a fundamental and enabling technique in 3D vision and graphics which has widespread applications. Despite many research advances in recent years, it still remains to be technically challenging, especially for 3D dynamic, densely-sampled facial data with a large number of degrees of freedom (necessarily used to represent rich and subtle facial expressions). Traditional non-rigid registration methods typically use a topology-stable template to register with the target, without taking the level of the scanned objects' detail into consideration. This will lead to bad registration or redundancies in the result. Motivated by this problem, we propose a new topology-adaptive non-rigid registration method for 3D facial scans. On the basis of analyzing previous works, our method solves this problem of traditional methods by combining the advantages of non-rigid registration and mesh subdivision/simplification. As a result, it not only reduces the redundancy of registered outputs effectively but also guarantees the accuracy of registration by adding or removing triangles of the template models. Fig. 1 shows the iterative procedure of our technique.

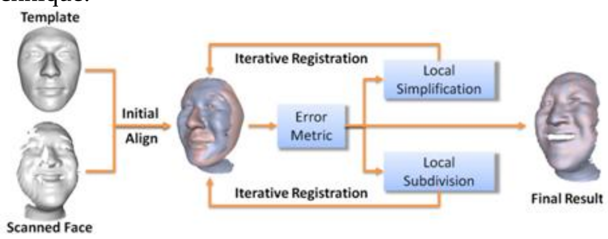

Fig. 1. The workflow of topology-adaptive non-rigid registration.

The main contributions of our paper are: First, we present a low-cost, real-time 3D scanning system that operates by stereo phase-shift, it utilizes low cost devices to capture range images of faces in real-time. Second, a new topology-adaptive strategy for non-rigid registration of 3D facial scans is devised, which combines the mechanism of non-rigid registration and mesh subdivision/simplification.

The rest of the paper is organized as follows: In Section 2 we discuss related works. A structured-light based scanning system for data preparation is documented in Section 3. In Section 4, we introduce our topology-adaptive non-rigid registration technique based on the analysis of traditional methods. Experimental results are discussed in Section 5, and we conclude our paper in Section 6.

II. RELATED WORKS

Non-rigid registration of surfaces is a non-trivial problem which is ill-posed since there are numerous mappings from one surface to another. A tremendous amount of attention has been given to this problem.

Landmark-based methods are quite common due to their simplicity. Correspondence computing is the key challenge in those methods, and Thin-plate spline (TPS) [1], [2] or radial basis function (RBF) [3] interpolation are commonly used. Several papers [4], [5], [6], [7] proposed to use local invariant shape descriptors to compute a one-to-one mapping. However, detecting landmarks and correspondences can be problematic especially in the presence of missing data and noises. Other papers [8], [9], [10], [11] proposed to compute isometric-invariant embeddings of the original shapes in a low-dimensional Euclidean space and to establish the correspondence using rigid registration algorithms. These methods tend to be costly and, moreover, fail for incomplete data.

A recent class of non-rigid scan data registration algorithms is based on iterative solvers. The source shape is deformed iteratively until an optimal alignment is achieved. Several methods are extensions of the classic ICP algorithm [12], [13]. In [2] the discontinuity issue was resolved by

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incorporating a global TPS warp. A generalization of this method was proposed in [14]. Hao et al [15] proposed a global correspondence optimization method for non-rigid registration of scans, and Huang et al [16] solved the iterative registration under the Isometric deformation scheme. However, among all these proposed methods little has considered about the complexity of registration target, and only a topology-stable template is used in the registration procedure. In contrast, our method introduces the concept of adaptive topology into the registration iteration. It changes the local topology of template adaptively to match with the complexity of scan and therefore avoids these problems.

III. Data Preparation

A. Structured-light 3D Scanning

3D reconstruction using stereo cameras is a popular research topic, and many algorithms have been developed in the past. Structured light scanning system replaces one camera by a projector which illuminates the scene with one or more patterns. Phase-shift is one of the popular structured light techniques, as it allows for highly accurate and dense reconstructions. In this paper we adopted the phase-shift structured-light 3D scanning technology to prepare the scan data. Fig. 2 shows the scanned range images and directly triangulated point clouds of five people's faces.

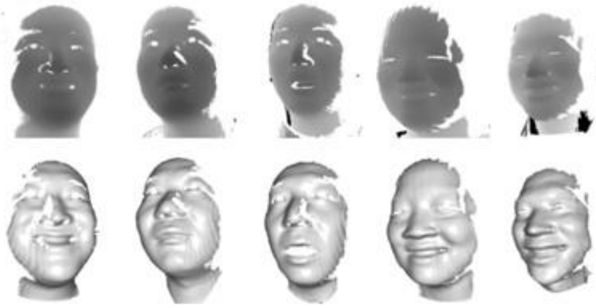

Fig. 2. Scanned faces using our phase-shift scanner

IV. Topology-Adaptive Non-Rigid Registration

A. Deformation Model

Iterative non-rigid registration methods typically consist of deformation model and certain target constraints [13,15]. Deformation models have been studied in great detail and we refer to [17,18,19] for a good overview. The deformation scheme used directly determines the quality of registration results, and our model favors membrane model in this paper since it results in more natural deformations with compare to minimizing vertex displacement differences directly [20]. We represent deformations with displacement vectors $d_i = f(v_i) = \tilde{v}_i - v_i$ for each mesh vertex v_i and deformed mesh vertex $\tilde{v}_i$. Deformation smoothness is achieved by minimizing a membrane energy on the displacement vectors, using the cotangent discretization of the Laplace-Beltrami operator:

$$E_{\text{smooth}} = \sum_i \|\Delta d_i\|^2 \quad (1)$$

$$\Delta d_i = \frac{1}{\mathcal{A}_i} \sum_{v_i \in \mathcal{N}(v_i)} \frac{1}{2}\left(\cot\alpha_{ij} + \cot\beta_{ij}\right)(d_j - d_i) \quad (2)$$

where α_{ij} and β_{ij} are the two angles opposite to the edge (v_i, v_j), and $\mathcal{A}_i$ is the Voronoi area of vertex v_i.

B. Energy Minimization

Before registration, several marker points $m_i (i = 1,2,3 \ldots)$ as sparse correspondence for initial registration of the template and the scan are manually labelled. And this correspondence forms the sparse error energy term as $E_{\text{corr}} = \sum_{i=1}^{N} \|v_i - m_i\|_2^2$. The correspondence energy term can only warp the templates roughly towards the shape of target scans. We also need a dense fitting term to deform the remaining vertices to approximate the range data accurately. Kd-tree structure was used to search for the closest point $\mathcal{cp}_i$ of each vertex v_i, and the dense fitting term is formulated as[21]:

$$E_{\text{fit}} = \sum_{i=1}^{N} w_i \left(\left| n_{\mathcal{cp}_i}^{T} (v_i - \mathcal{cp}_i) \right|^2 + \|v_i - \mathcal{cp}_i\|_2^2 \right) \quad w_i = 0 \text{ or } 1 \quad (3)$$

Data missing is inevitable in the target scan, therefore some vertices cannot find the correct closest points. If the distance of a closest point pair is larger than a threshold, we set the corresponding weights to $w_i = 0$. $n_{\mathcal{cp}_i}^{T}$ is the normal of the closest point $\mathcal{cp}_i$. Finally all the three energy terms are combined, yielding the whole deforming energy function:

$$E_{deform} = \lambda_{fit} E_{fit} + \lambda_{corr} E_{corr} + \lambda_{smooth} E_{smooth} \quad (4)$$

where λ_{fit}, λ_{corr} and λ_{smooth} are used to control the weights of each energy term at each iteration. In our experiment, λ_{corr} is large at beginning and then gradually reduces while λ_{fit} is just the reverse. λ_{smooth} remains unchanged in the whole process.

C. Topology Adjustment

The topology of the template is always different from the target model, especially for scan data. Therefore only a topology-stable template is not sufficient for accurate registration. For instance, if the target model is rich in detail while the template is a coarse triangle model (Fig. 3), the aligned results will definitely be unable to characterize the detail of target model. Otherwise, if the target is coarse while the template is dense triangulated, the alignment may cause redundant vertices. In addition to this problem, triangle split is not supported by traditional technique, therefore areas which contain a hole (such as mouth) in the target model can cause distortion in the results (Fig.4).

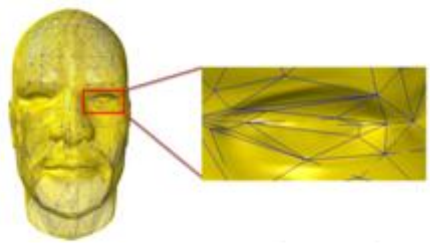

Fig. 3. Register a coarse mesh to complex target.

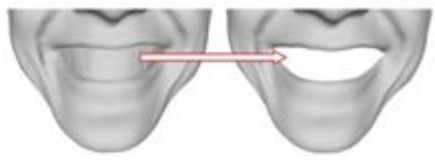

Fig. 4. Distortion in the region of mouth

Motivated by this observation, we introduce the concept of adaptive topology into the registration iteration. The principle of our technique is changing the local topology of template adaptively to match with the complexity of scan. After each step of non-rigid registration, the closest point error will be computed over the mesh. We used a relative error metric to control the simplification/subdivision of next iteration:

$$RE_i = \frac{\|v_i - cp_i\|_2^2}{Scale_{scan}} \quad (5)$$

where the $Scale_{scan}$ represents the diameter of the bounding sphere of target scan model. A threshold μ is set to control the required accuracy of result. A simplified iteration is depicted in Fig. 5 as pseudo-code. By changing the threshold, users can directly customize the end condition of optimization and the accuracy of result.

For the problem of hole distortion, first we need to judge whether the hole is mouth or other data loss. Image-based facial landmarks detection can easily do this with the facial texture acquired by our scanning system. Then we keep watch on all the edges of deformed template at each iteration. If the length of an edge e_i stretches over a default constraint: $l_{ei}^{cur} > \varepsilon \cdot l_{ei}^{orig}$, we search for the closest point on the target scan to the middle point of the edge e_i. If the closest distance satisfies $d_{ei} \geq 0.5 \cdot l_{ei}^{cur}$, we consider the edge to be redundant and delete it.

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For all the vertices of deformed template
    Compute RE_i for each vertex v_i
    If RE_i > μ
        Subdivide the vertex v_i
    If RE_i < μ/2
        Merge vertices
End
```

Fig. 5. The pseudo-code of iteration

V. Experiment and Results

To illustrate the performance of our proposed technique, we conduct a series of experiments on real scans. The results are then compared with Hao's global correspondence optimization non-rigid registration method described in [15], which stands for the state of the arts and also use a combination of point-to-plane and point-to-point metric but with no topology changed. Our proposed non-rigid registration algorithm implementation was performed on a 2.67 GHz Quad-Core Intel i5 CPU machine with 2GB RAM.

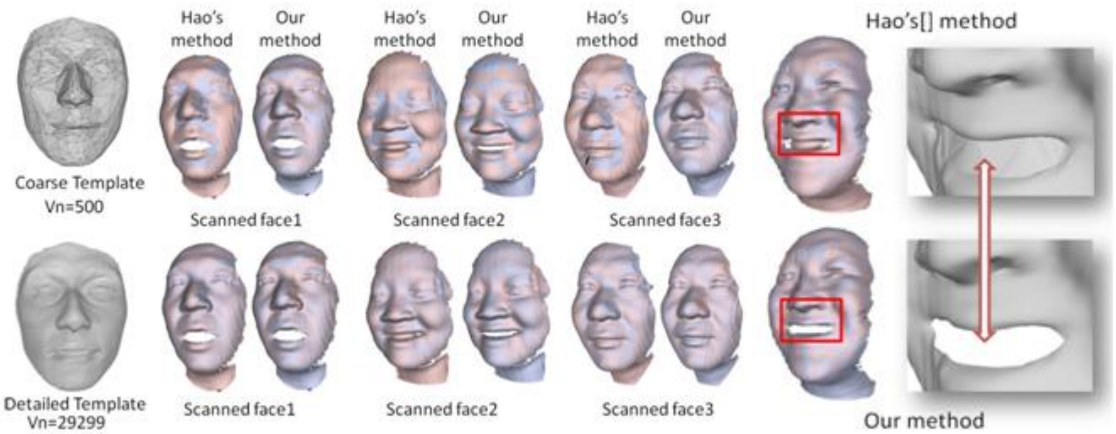

Fig. 6. Registration results using Hao's and our method

Fig. 6 and Table I show the visual and quantitative experiment results of Hao's and our method using coarse and detailed templates separately. For coarse template, our results are more accurate by subdivide the mesh to an appropriate topology. For detailed template, our results are more simplified while guaranteeing acceptable accuracy. Besides, the mouth area are correctly split using our method.

TABLE I: Quantitative Results of Hao's and Our Method (VN Is the Number of Vertices)

	Hao's method with coarse template		Our method with coarse template		Hao's method with detailed template		Our method with detailed template	
Scan1	RE=3.1%	Vn=500	RE=0.24%	Vn=6124	RE=0.11%	Vn=29299	RE=0.14%	Vn=12583
Scan2	RE=4.5%	Vn=500	RE=0.18%	Vn=5837	RE=0.06%	Vn=29299	RE=0.09%	Vn=10439
Scan3	RE=2.9%	Vn=500	RE=0.29%	Vn=6270	RE=0.12%	Vn=29299	RE=0.17%	Vn=13511

VI. Conclusions

Non-rigid registration of scanned model is a fundamental and enabling technique in 3D vision and graphics which has widespread applications. In this paper we have introduced a non-rigid registration algorithm for range scans of faces. Our method is designed for constructing smooth, triangulated facial models from scanned point cloud or range images. The key insight of this paper is that topology-stable template is insufficient for accurate non-rigid registration for all type of scans. Therefore topology adjustment is integrated into the whole iterative procedure of scan alignment. The experiment results showed that our method can achieve acceptable accuracy while maintaining reasonable amount of vertices in the aligned results. As future work we plan to investigate the use of adaptive topology in other scenarios and apply our method to non-rigid registration of other types of scanned objects.

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