Computers & Graphics 34 (2010) 209–218

Contents lists available at ScienceDirect

Computers & Graphics

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

Technical Section

Orienting unorganized points for surface reconstruction

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ARTICLE INFO

Article history:
Received 3 December 2009
Received in revised form
29 January 2010
Accepted 7 March 2010

Keywords:
Orientation
Consistency
Unorganized points
PCA
Surface reconstruction

ABSTRACT

We address the problem of assigning consistently oriented normal vectors to unorganized point cloud with noises, non-uniformities, and thin-sharp features as a pre-processing step to surface reconstruction. The conventional orienting scheme using minimal spanning tree fails on points with the above defects. Different from the recently developed consolidation technique, our approach does not modify (i.e., down-sampling) the given point cloud so that we can reconstruct more surface details in the regions with very few points. The method consists of three major steps. We first propose a modified scheme of generating adaptive spherical cover for unorganized points by adding a sphere splitting step based on eigenvalue analysis. This modification can better preserve the connectivity of surface generated from the spheres in the highly sparse region. After generating the triangular mesh surface and cleaning its topology, a local search based algorithm is conducted to find the closest triangle to every input points and then specify their orientations. Lastly, an orientation-aware principle component analysis step gives correct and consistently oriented normal vectors to the unorganized input points. Conventional implicit surface fitting based approach can successfully reconstruct high quality surfaces from the unorganized point cloud with the help of consistently oriented normal vectors generated by our method.

1. Introduction

The reverse engineering problem for reconstructing three dimensional models in a computer system from unorganized points that are generated by 3D surface scanning devices has been a subject of intensive research for many years. The scanned 3D surface represented by an unorganized point cloud is typically noisy, contains holes, and has high variations in point density. Oriented normals at the points play a critical role in surface reconstruction. It is because that the oriented normals define the reconstructed surface to the first order and identify the inside/outside information. As will be shown in our tests below, the oriented normals become extremely important at the regions with very sparse points. Also, to generate correctly oriented normal vectors on the points in such regions is a very tough job. The conventional methods using *minimal spanning tree* (MST) (e.g., [1]) or Voronoi diagram (e.g., [2–4]) fail. Some recent researches consider estimating normals from captured images using photometric stereo [5,6], which however suffers from the unideal acquisition conditions like specular reflections, material artifacts, and shadowing. The most recent work presented in [7] does not assign normal vectors directly to the given points. It first adopts a weighted locally optimal projection operator to produce a set of denoised and evenly distributed particles over the original point cloud, and then conducts a priority-driven normal propagation scheme to assign normal vectors to the particles. This down-sampling strategy actually further removes limited information of underlying surfaces from those highly sparse regions, therefore the reconstructed surface in such regions will not be as good as ours (see Fig. 1). Our approach proposed in this paper can assign consistently oriented normal vectors to the scattered points so that the downstream reconstruction algorithm can successfully generate surface in the regions with highly sparse points.

To orient unorganized points effectively and efficiently, we develop two techniques by extending the integrating approach for meshing scattered point data [8]. First, a modified scheme is proposed to generate *adaptive spherical cover* (ASC) for unorganized points by adding an eigenvalue analysis based sphere splitting step. With this step, our approach can better preserve the surface's connectivity in the regions with highly sparse points. After getting the spherical cover for scattered points, the triangulation and topology cleaning procedure [8] can generate a triangular mesh surface M roughly presenting the underlying surface S. Although this mesh M is not a good approximation of S, it gives a very robust evidence for assigning the orientation of input points. A straightforward way is to find the closest point $\mathbf{c}_p$ on M for each input point $\mathbf{p}$, then the normal vector $\mathbf{n}_{\mathbf{c}_p}$ of $\mathbf{c}_p$ on M is assigned as the normal vector of $\mathbf{p}$. Nevertheless, as M is an inaccurate approximation of S, such normal vectors give inaccurate surface information to the downstream mesh reconstruction algorithm (e.g., [9]). Therefore,

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doi:10.1016/j.cag.2010.03.003

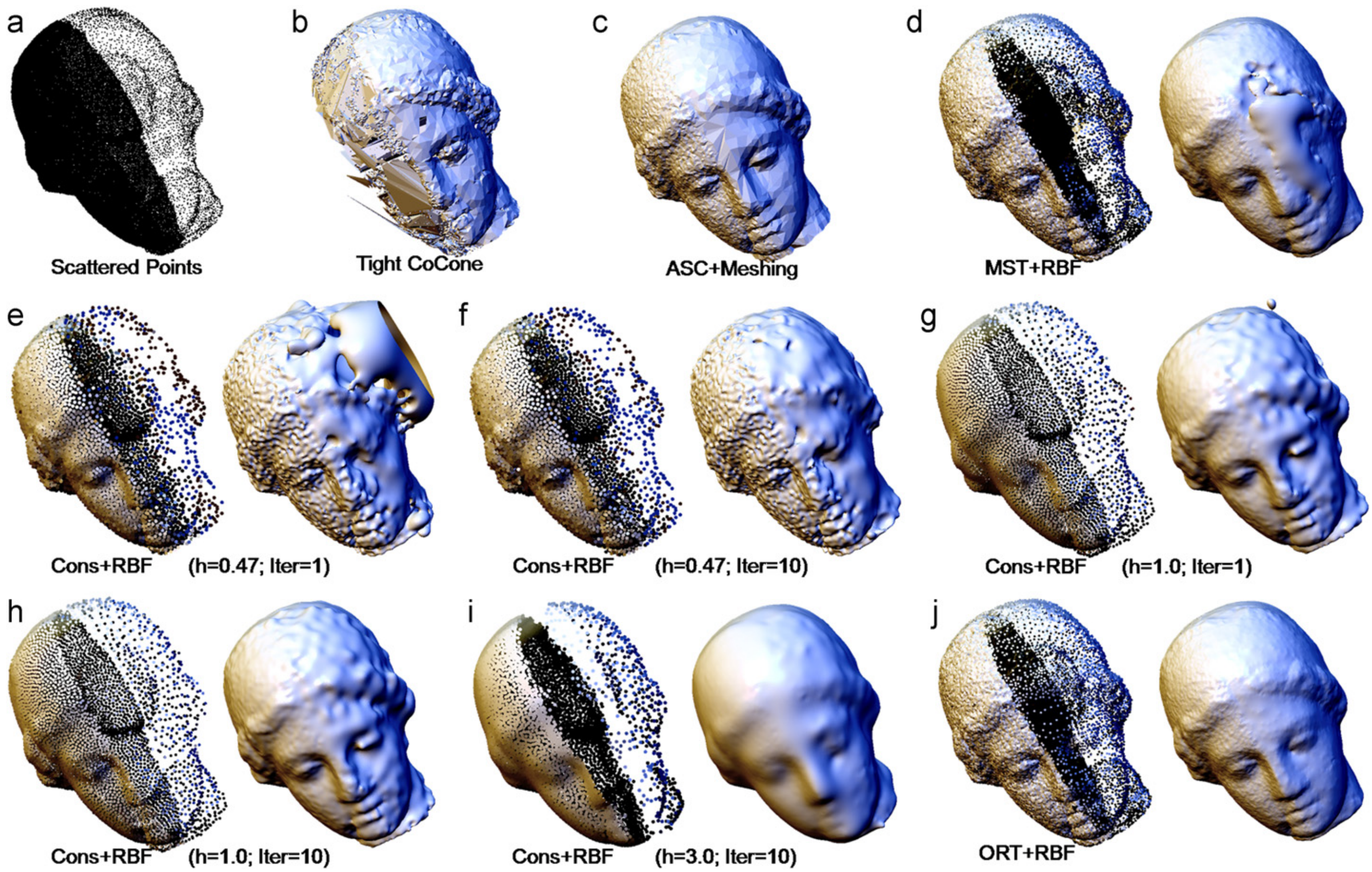

Fig. 1. Surface reconstruction results on (a) the Venus model (72.5k points) with noises and non-uniform point density by different approaches, including: (b) Tight CoCone [4], (c) the integrating approach with *adaptive spherical cover* (ASC) followed by a meshing step [8], (d) the conventional *minimal spanning tree* (MST) based normal estimation [1] followed by a *radial basis function* (RBF) based surface reconstruction [9], (e)–(i) the point cloud *consolidation* (Cons) [7] followed by RBF-based surface reconstruction, and (j) our orienting approach (ORT) with RBF-based reconstruction. For those resultant mesh surfaces generated by RBF, the left picture shows the direct rendering of points (or particles for [7]) with estimated normal vectors. From the result of MST, it is easy to find that many points are displayed in black since their orientations are detected incorrectly. In the results of Cons [7] ((e)–(i)), *h* is a parameter for the support size of particles and *Iter* stands for the number of iteration steps. The failure of Tight CoCone, ASC+Meshing and MST+RBF is mainly caused by the sparseness of input points. Producing a denser and more uniformly distributed set of points can improve the quality of reconstructed surfaces by them.

instead of assigning $\mathbf{n}_{\mathbf{c}_p}$ to $\mathbf{p}$, we only let $\mathbf{p}$ hold the orientation of $\mathbf{n}_{\mathbf{c}_p}$—thus, we name our method as *orienting* approach (ORT). An orientation-aware *principle component analysis* (PCA) step is adopted to assign correct and consistently oriented normal vectors to the unorganized points. Moreover, the ASC constructed in the first step will be employed to speed up the closest point search on *M*. The experimental results demonstrate that our approach can successfully orient the unorganized point clouds for various models—so that conventional schemes like [9] can reconstruct a proper surface for the input data. Fig. 1 shows a comparison of the results between other approaches and ours on a Venus head model with non-uniform point density and noises. Our approach (ORT+RBF) gives the best reconstruction result. The good performance of our approach is benefited by (1) the proposed framework of using adaptive ASC to give the consistent orientation of points and (2) the newly developed sphere splitting step based on eigenvalue analysis.

2. Related work

The existing work in the literature can be classified into two major groups: (1) computational geometry approaches and (2) volumetric reconstruction techniques, which will be reviewed below.

The computational geometry approaches are usually based on the Voronoi diagram of a given point cloud and reconstruct a mesh surface by directly linking the input samples. Normal information is not required. Amenta et al. [2] gave a provable guarantee of reconstructing a correct model given a minimum sampling density dependent on the local feature size. The approach was further extended to be able to handle noisy input in [10]. However, as they did not remove outliers, the quality of the resultant meshes was not good. Several variations of [2] are available in [3,4,11,12]. When applying these algorithms to practical data sets, there are two difficulties. First, both memory and time cost to compute Voronoi diagram are expensive. Second, such approaches request the input points to satisfy the *d*-covering requirement—i.e., the point set *S* sampled from the model *H* has any point $\mathbf{p}$ on *H* that can find a point $\mathbf{q} \in S$ such that $\|\mathbf{p}-\mathbf{q}\| \le d$, where *d* is less than the smallest feature's size on *M*. This is hard to be satisfied, especially in the regions with highly sparse points and with noises embedded in *S* (see the examples shown in Figs. 1 and 16 where the Tight CoCone approach [4] fails). To the best of our knowledge, the integrating approach presented in [8] is a very good approach that can handle the above difficulties while does not need the input points to be equipped with normal vectors. However, their algorithm does not preserve the connectivity of underlying surfaces in the regions with very few points. Our extension of [8] contributes to this.

The volumetric reconstruction techniques attempt to build a signed implicit function that interpolates or approximates the point cloud samples [1,9,13–18], and then extract its isosurface using, e.g., the Marching Cubes algorithm [19]. Nevertheless, the computation of such a signed implicit function requires the point