LETTER

HSWIS: Hierarchical Shrink-Wrapped Iso-Surface Algorithm

Young-Kyu CHOI[†a)], ***Member and*** **Eun-Jin PARK**[†], ***Nonmember***

SUMMARY A new hierarchical *isosurface* reconstruction scheme from a set of tomographic cross sectional images is presented. From the input data, we construct a hierarchy of volume, called the *volume pyramid*, based on a *3D dilation filter*. After extracting the base mesh from the volume at the coarsest level by the *cell-boundary method*, we iteratively fit the mesh to the *isopoints* representing the actual isosurface of the volume. The SWIS (*Shrink-wrapped isosurface*) algorithm is adopted in this process, and a mesh subdivision scheme is utilized to reconstruct fine detail of the isosurface. According to experiments, our method is proved to produce a hierarchical isosurface which can be utilized by various multiresolution algorithms such as interactive visualization and progressive transmission.
key words: *surface reconstruction, multiresolution isosurface, cell-boundary representation, and shrink-wrapping scheme*

1. Introduction

Isosurface reconstruction is a very common and useful tool for the visualization of volume data. Lorensen and Cline [1] have proposed a novel method, called the *marching cubes (MC)* algorithm, which can obtain high resolution *isosurface* from 3D medical data. Since its original conception, it has been the subject of much further research to improve its quality (including the ambiguity [2] in surface definition) and its performance on large data set. This letter tries to focus on the latter issue of MC.

In the marching cube algorithm, the output mesh approximating the isosurface of a volume can easily consist of millions of triangles. Lots of post processing techniques have been proposed to reduce and to improve the mesh, including *decimation*, *simplification* and *remeshing* [3], [4], but they can be very expensive in time and memory consumption. On the other hand, extracting multiple resolution isosurfaces directly from the volume data can be a good solution for this problem. The need for *multiresolution isosurface* becomes apparent when such large data sets have to be visualized *interactively* as required by many applications such as image guided surgery or progressive transmission. In the field of interactive visualization, the isosurface extraction phase may be too slow and the mesh size can easily exceed the number of triangles that can be rendered at interactive frame rate without multiple resolutions.

Several algorithms addressed the use of adaptive hierarchies of the volume data set to improve the performance of MC [5], [6]. Labsik et al. proposed a method utilizing a hierarchy on the input volume data [7]. They create a hierarchy of volumes by down-scaling the input volume data. Then they extract the isosurface on the coarsest resolution by MC, and fit the mesh onto the isosurface at the finer levels of the volume hierarchy. In the projection step, they estimated the *normal vector* for each mesh point, and used the *shortest signed distance* of the point to the isosurface to move the mesh point at level *l+1* to the isosurface at level *l*. Although their method exploits multiresolution capability, they had to estimate isosurfaces at the finer levels for the projection process, and the distance function cannot be properly defined everywhere. Furthermore it is not free from the ambiguity problem in surface definition process (possible “holes” in the resulting surface) because they adopted MC for the base mesh.

Recently, we proposed a new isosurfacing method based on a relaxation scheme [8]. Differently from the MC, it does not extract the isosurface directly from the voxel data but calculates the *iso-density point (isopoint)* first. After building a coarse initial mesh approximating the ideal isosurface by the CBM (*cell-boundary method*) [9], it metamorphoses the mesh into the final isosurface by the *shrink-wrapping process*. Compared with the MC algorithm, their method is robust and does not make any cracks on surface. Furthermore, since it is possible to utilize lots of additional isopoints during the surface reconstruction process by extending the adjacency definition, theoretically the resulting surface can be better in quality than the MC algorithm.

In this letter, we try to extend our previous work [8] to exploit the multiple resolution isosurface by adopting the scheme proposed by Labsik et al. Instead of using MC, our method extracts the initial mesh by the CBM at the coarsest level. We also simplify the projection process by using the *isopoints* rather than the *isosurface*.

This letter organized as follows. The concept of the volume pyramid is introduced and the initial mesh generation technique from the coarsest volume is provided in Sect. 2. Section 3 describes our multiresolution surface fitting scheme. Experimental results are given in Sect. 4, and Sect. 5 concludes this letter.

2. Volume Pyramid and the Initial Mesh

The multiresolution approach considered in this letter is based on the *volume pyramid*. Let us consider a volume data V^l defined on a regular grid G^l of dimensions n_x, n_y and n_z, where l represents the *level* of the volume data (0 for

Manuscript received July 31, 2008.
[†]The authors are with the School of Information Technology, Korea University of Technology and Education, Rep. of Korea.
a) E-mail: ykchoi@kut.ac.kr
DOI: 10.1587/transinf.E92.D.757

the original volume). The grid at *level 0* can be denoted as $G^0 = \{(x_i, y_j, z_k) | 0 \le i \le n_x, 0 \le j \le n_y, 0 \le k \le n_z\}$, with $x_i = x_0 + ih$, $y_j = y_0 + jh$ and $z_k = z_0 + kh$ for the same grid size h.

Assume that an input volume data V^0 is given on a grid G^0. The *volume pyramid* defined by a set of volume data $\{V^0, V^1, \cdots, V^{L-1}\}$ can be computed by iteratively down-sampling V^0 by a factor of two. Lots of 3D filters, such as $2 \times 2 \times 2$ mean, median and dilation filters, can be applied to convolve the voxels at level $l - 1$ to estimate the down-sampled voxel value at level l. Since the densities of the object we want to reconstruct are usually larger than those of the background voxels, the dilation filter selecting the largest density from the 8 voxels could be the best choice [7]. For thin parts of the object as shown in Fig. 1 (a), the mean filter may omit some isosurface as shown in Fig. 1 (b), and consequently may result in topological holes on the surface mesh as shown in Fig. 2 (a). In the case of the dilation filter, the down-sampled volume is proven to envelop the isosurface extracted from the finer level because it has a growing effect as shown in Fig. 1 (c). Figure 2 (b) illustrates isosurface reconstruction result by the cell-boundary method [9] from the down-sampled volume using the dilation filter.

The dilation filter for constructing the volume pyramid may modify the surface topology, such as removing small holes in the upper volume data. But, in general, it is appropriate for the data sets we consider because they are topologically simple. For a given volume data V^0, we can extract the volume pyramid by convolving the dilation filter iteratively to the voxels at the lower levels. After building the volume pyramid, the initial mesh M^{L-1} should be constructed from the volume at the top-most level of the pyramid. We adopted the cell-boundary method (CBM) for this purpose [9]. The CBM does not provide a highly detailed surface like MC, but is quite robust for approximating surface from voxel data in that it provides a unique representation without having any ambiguity in surface definition. The surface complexity (number of triangles) is also simplified by 40% ∼ 50% compared with the MC. Thus it can be a good choice for acquiring the initial base mesh of the isosurface on the coarsest resolution.

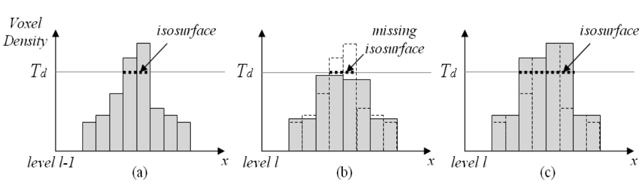

Fig. 1 Filtering the input volume: (a) original voxels (level $l - 1$), (b) voxels after mean filtering (level l) and (c) after dilation filtering (level l).

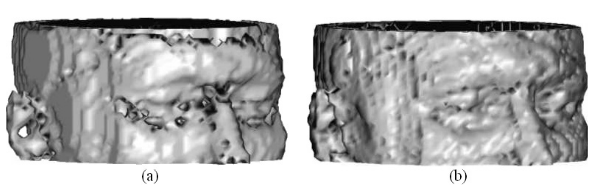

Fig. 2 Isosurfaces by CBM after down-sampling by: (a) the mean filtering, and (b) the dilation filtering.

3. Surface Fitting and Subdivision

Since the initial mesh by CBM does not provide a highly detailed surface and the growing effect of the dilation filter, we have to fit the mesh onto the isosurface. We adopted our previous work, called the *shrink-wrapped iso-surface* (SWIS) method, for this purpose [8].

Assume that an initial mesh M^l approximating the isosurface of a volume data V^l at level l is given. We first extracts the *isopoints* P^l from V^l. To simplify the fitting process, SWIS uses the isopoints as the *reference points* for the fitting process: actual 3D points assumed to be sampled from the ideal isosurface of V^l. Furthermore, it can overcome the O(1)-adjacency restriction of MC by adopting higher order of adjacency such as O(2) and O(3)-adjacency in the isopoints extraction step. (Udupa et al. used the term O(1)-adjacent when a pair of voxels share a face [8]. In O(2)-adjacency, two voxels sharing an edge are also defined to be adjacent and O(3)-adjacent when they share a vertex.)

The initial mesh M^l is then iteratively metamorphosed into the isopoint P^l by the *shrinking* and *smoothing* operations. The shrinking step is applying the attracting force to each vertex of the mesh. For a vertex q_i of M^l, the *attracting force vector* $f = q_i - p_i$, where p_i is the nearest isopoint of q_i, pushes the mesh vertex q_i toward p_i as follows.

$$q_i \leftarrow q_i + \alpha f$$

The weight α (0.0 to 1.0) controls the amount of the attracting force.

The smoothing step tries to relax the shrink-wrapped surface to achieve a uniform vertex sampling. We have adopted the same method used in SWIS, which is employing the approximation of Laplacian L. After the shrink-wrapping step, we finally acquire the resulting mesh at level l, denoted as M^l_{fit}, which represents the isosurface of the volume at the level.

To produce the initial mesh at the next finer level, the isosurface at the upper level should be transformed into a mesh on the next finer resolution. We first scale up the mesh M^l_{fit} by moving all of the vertices by factor of two. Furthermore, the mesh should be subdivided to capture local detail of the isosurface at the finer level. We adopted the technique proposed by Loop [10], which iteratively divides a triangular patch into four. After these steps, the mesh M^l_{fit} on G^l is transformed into the initial mesh M^{l-1} at the finer level.

By applying the surface fitting procedure iteratively to the initial mesh at the next finer level, we can construct the isosurface at level $l-1$, denoted as M^{l-1}_{fit}, and then M^{l-2}_{fit}, and so on, until we finally arrive at level 0. Consequently, the multi-resolution isosurface model, a group of isosurfaces at each level $\{M^0_{fit}, M^1_{fit}, \cdots, M^{L-1}_{fit}\}$, can be reconstructed.

4. Experiments

The proposed method has been implemented in C++, and runs on a Pentium-PC under Windows-XP. For the experiment, we used the volume data from the Volvis (http://www.volvis.org) and the University of Iowa (http://radiology.uiowa.edu).

Figure 3 shows experimental result for the head data from Volvis (128 slices of $256 \times 320 \times 8$ bit images). After building the volume pyramid ($L = 4$), the initial mesh M^l at the coarsest level ($l = 3$) is extracted by the CBM algorithm as shown in (a). We extract the isopoints P^3 in O(3)-adjacency from the volume data at level 3, and apply the *surface fitting process* to shrink the initial mesh M^3 onto the isopoints P^3 representing the isosurface of V^3. During this step the crude initial mesh is metamorphosed into the smooth surface representing the isosurfaces of V^3 at the coarsest level (M^3_{fit}) as shown (b). For the initial mesh M^2 at the next finer level ($l = 2$), the mesh *scale-up* and *subdivision* steps are applied to M^3_{fit} as shown in (c). M^2 is further transformed into the isosurface M^2_{fit} as shown in (d). The isosurfaces at the next finer levels (M^1_{fit}, M^0_{fit}) can be extracted by applying the same procedure.

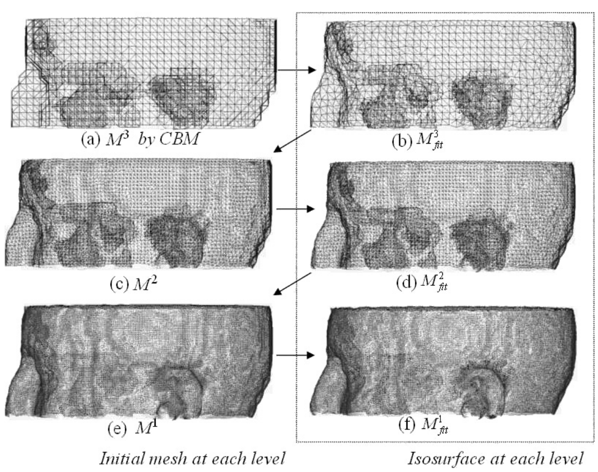

Fig. 3 Surface construction result from the *head* data.

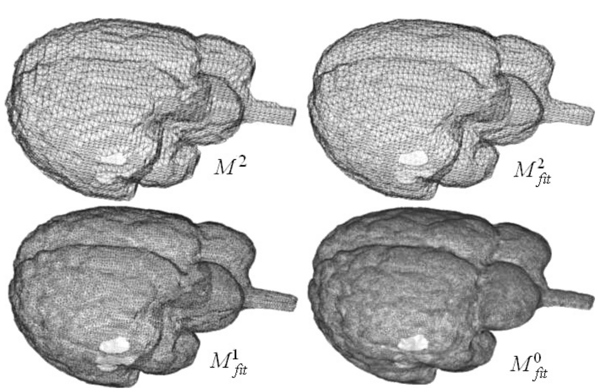

Fig. 4 Multiresolution isosurface construction scheme for the *brain* data.

Figure 4 illustrates multiresolution isosurface construction result for the *brain data* (MR_SEGBRAIN) from the collection of 8-bit medical datasets of University of Iowa (128 slices of $256 \times 256 \times 8$ bit images). After approximating the initial mesh M^l at the coarsest level ($l = 2$), the isosurface for each resolution was extracted by the proposed method. Figure 5 shows comparison of our method with MC for the brain data. With lots of jagged surfaces as shown in the figure, the resulting mesh constructed by MC contains cracks on surface. On the other hand, although it does not contain any cracks, our method seems to be not satisfactory in the regions of high curvature compared with the MC algorithm. Since our method produces less than 50% of triangles compared with MC, it can miss some regions of highly detailed surface.

Table 1 lists the surface reconstruction summary and Table 2 summarizes the actual computation times for the brain data. Although the overall computation time of our method in O(3)-adjacency is about 8 times slower than the MC algorithm, the processing times at the coarse levels are much faster than the MC, and the number of surface patches at the coarse levels are much smaller than MC. Consequently we expect that our method can be successfully applied to the interactive visualization applications such as image guided surgery and progressive transmission.

5. Conclusion

The need for multiresolution isosurface becomes apparent when large data sets have to be visualized *interactively*. In this letter, we proposed a new hierarchical isosurface reconstruction scheme from cross sectional images. From the input volume data, we construct a volume pyramid based on a 3D dilation filter, and extract a base mesh from the coars-

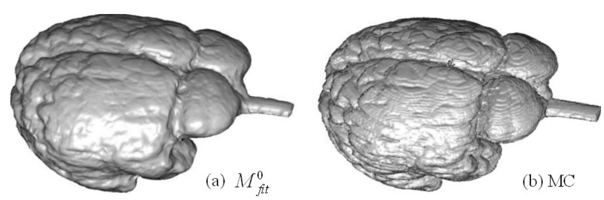

Fig. 5 The *brain* data: (a) reconstruction result by our method, (b) reconstructed surface by MC.

Table 1 Summary of the experimental results.

method	total levels	adja-cency	final isosurface ($l = 0$)		intermediate isosurface	
					$l = 1$	$l = 2$
			pts	tri	tri	tri
MSWIS	3	O(3)	78406	156832	39208	9802
MC	1	O(1)	174326	344120	none	none

Table 2 Compariton of exection time for the brain data [sec].

method	MSWIS				MC
	level 2	level 1	level 0	overall	
execution time	≤ 0.3	≤ 0.9	14.7	15.9	2.1

est volume with the *cell-boundary method*. We iteratively fit this mesh to the isopoints representing the ideal isosurface using the *shrink-wrapping scheme*, and finally subdivide the mesh to represent fine detail of the isosurface. According to experiments, our method works well for constructing multiple resolution isosurface for the topologically simple data set.

Although it does not contain any cracks, our method seems to be not satisfactory in the regions of high curvature compared with the MC algorithm. Furthermore, the hierarchical isosurface scheme usually may change topology of the isosurface as small holes can disappear. The subdivision process also can be improved by adopting error-driven adaptive subdivision schemes. They remain problems to be addressed in future work.

References

[1] W. Lorensen and H. Cline, "Marching cubes: A high resolution 3-d surface construction algorithm," Comput. Graph., vol.21, no.4, pp.163–169, 1987.
[2] M. Durst, "Letters: Additional reference to marching cubes," Comput. Graph., vol.22, no.2, pp.72–73, 1988.
[3] W. Schroeder, J. Zarge, and W. Lorensen, "Decimation of triangle meshes," Proc. 19th Annual Conference on Computer Graphics and Interactive Techniques, pp.65–70, 1992.
[4] S. Kim, C. Kim, and D. Levin, "Surface simplification using a discrete curvature norm," Comput. Graph., vol.26, pp.657–663, 2002.
[5] T. Gerstner and R. Pajarola, "Topology preserving and controlled topology simplifying multiresolution isosurface extraction," IEEE Visualization 2000, pp.259–266, 2000.
[6] G. Weber, O. Kreylos, T. Ligocki, H. Hagen, B. Hamann, and K. Joy, "Extraction of crack-free isosurfaces from adaptive mesh refinement data," Proc. VisSym 2001, pp.25–34, 2001.
[7] U. Labsik, K. Hormann, M. Meister, and G. Greiner, "Hierarchical iso-surface extraction," Journal of Computing and Information Science in Engineering, vol.2, no.4, pp.323–329, 2002.
[8] Y. Choi and J. Hahn, "Shrink-wrapped isosurface from cross sectional images," IEICE Trans. Inf. & Syst., vol.E90-D, no.12, pp.2070–2076, Dec. 2007.
[9] E. Lee, Y. Choi, and K. Park, "A method of 3D object reconstruction from a series of cross-sectional images," IEICE Trans. Inf. & Syst., vol.E77-D, no.9, pp.996–1004, Sept. 1994.
[10] C. Loop, Smooth subdivision surfaces based on triangles, M.S. Mathematics Thesis, University of Utah, 1987.