Title:
Comparative Study of 3D Reconstruction Methods for Medical Imaging

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Introduction:

This paper focuses on 3D surface reconstruction techniques applicable to MR images. This area plays an important role in providing realistic 3D models of anatomy or structure of human being bodies, and is very useful for medical diagnosis, visualization, and model-based therapy planning. It can also be applied for other purposes like virtual education, surgical planning and further analyses. Imaging technology such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), typically provide 2D cross sectional images that are spaced evenly on individual slices. This data allows the reconstruction of a 3D model that can be used for many applications: visualization, diagnostic aid and simulation of the propagation of physiological elements. A precise 3D reconstruction model is important since it can reflect properly the structural characteristics of organs and ensure an accurate anatomical evaluation and precise surgical planning enabling thus higher efficiency in preoperative assessment. 3D surface reconstruction techniques extract polygonal surface from volume data which is obtained from cross-sectional MR images [5]. The primary goal is to create a triangular mesh, which fits to the segmentation boundary inside the volume. Historically, reconstruction techniques have been introduced with the famous Marching Cubes (MC) isosurface extraction algorithm [3].

In this paper, we present a comparison between four different reconstruction methods, two of them are based on the marching cube algorithm [8, 2] and the other two are contour based algorithms [1, 9]. The comparison allows to establish similarity, equivalence, or distinctness between the four methods. We evaluate the quality of each of the reconstruction method and determine how faithfully each model fits to the segmentation. All our tests and comparison are in 3D Slicer [6] and Slicer RT (extension that has been developed for the 3D slicer) [7].

In the following of this article, we present the four studied reconstruction methods and then we expose their results, advantages and limitations.

3D Reconstruction methods:

This section describes briefly the four reconstruction methods studied in this work : Flying Edges, Dual Marching cube, SlicerRT contour interpolation and MPU implicit models. All the four methods are tested, visualized and analyzed using an open-source software package 3D Slicer [6] and Slicer RT (source extension that has been developed for the 3D Slicer platform). 3D Slicer provides among others, tools for reconstructing and visualizing triangulated surface models. In the following, a description of each of the four methods is recalled.

Fig. 1: 3D reconstructed models from MRI images used for the study

Flying Edges (FE):

is an algorithm designed from the standard MC algorithm, in a way that is better optimized for multi-core processors [8]. It operates on a 3D grid of voxels and uses a lookup table from which the triangle configuration of each voxel is determined. The location and gradients of the surface vertices are approximated in the same way as MC. The difference between the two algorithms lies in how the volume data is processed. Whereas, the MC marches through all the voxels of the volume in one pass, FE uses multiple preprocessing passes. The first preprocessing stage marches through all the voxels along one dimension of the volume and determines which edges are intersected by accessing the iso-values stored in the volume. The second preprocessing stage determines which edges along the other two dimensions are intersected using informations gained in the first preprocessing stage. The third of the preprocessing stages allocates memory to contain the triangles and points, while the last stage calculates the intersection points and generates triangles. This process is available in 3D Slicer and we have used it to generate models shown in Fig. 1.

Dual Marching Cubes (DMC):

is an alternative strategy to generate 3D closed surface models by reconstructing quad only meshes from volume data. Quad faces are supposedly better shape than triangle ones. DMC relies on the lookup table introduced in [4] to produce a quad only mesh from a volume data such as a 3D grid. In our study, we used a novel algorithm using DMC [2] that consists of the reconstruction of that kind of mesh and a topological simplification to reduce the number of irregular vertices. The output of this algorithm is topologically consistent across cell borders, i.e it is watertight. To resolve ambiguous face, a new algorithm is used to correct them without using additional lookup tables. This DMC produces a quad only mesh stored in a halfedge data structure. The execution flow of this algorithm is divided in three main steps : 1) initialize buffers (for parallelize purpose); 2) compute the DMC mesh; 3) generate a halfedge data structure. The output can be smoothed by the same exact method as the FE inside 3D Slicer.

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Contour Interpolation (CI):

algorithm presented in [9] and implemented in SlicerRT, is a method used for creating 3D closed surface models from planar contours. The main idea of the algorithm is to interpolate between the adjacent cross-sectional contours using a mesh, going through four main stages. The first stage removes the keyholes from the set of contours to avoid errors in the triangulation process. The second stage determines which contours should be connected by triangles between each of the slices. The third stage of the algorithm computes the branching patterns for contours that posses a correspondence to multiple contours on an adjacent slice while the last stage triangulates the contours and seals the external contours to fill the gaps that are left in the surface model.

MPU Implicit models (MPU):

presented in [1] interprets the planar contours as points in R^3 and employs Multi-level Partition of Unity (MPU) implicit models to create a surface that approximately fits to the 3D points. The main idea is to subdivide the point set in space using an adaptive octree-based subdivision scheme, where the surface estimation of each partition is performed locally and the local implicit functions are blended together to produce the overall surface. Since the MPU requires surface normal information, the surface normal at each contour point is estimated from the binary volume, constructed from the set of contours as described in [1]. The implicit functions are approximated using local quadric functions, where the choice of the appropriate function depends on local surface features implied by the point normals. At each stage of the subdivision process, the local function's accuracy has to be evaluated and compared to a user-specified tolerance value (tol) in order to determine if the local implicit surface need to be refined. This method is implemented and added as a loadable module in SlicerRT and as seen in the next section it outperformed the existing method in slicer RT [9].

Comparison and Analysis:

In order to compare the four different methods in the same software, we have implemented the MPU algorithm for creating 3D closed surface models from planar contours in SlicerRT and added also the DMC in 3D Slicer.

The aim of the reconstruction methods studied is to produce a 3D model as close as possible to the data provided by the segmentation process. For each 3D model, we evaluate the distance between the segmentation and the produced mesh (i.e. the distance between each point of the segmentation to the nearest point of the 3D model). To compute the distance, we have added a comparison plugin to 3D slicer based on Hausdorff distance. Distance computation allows to evaluate the quality of reconstructions and determine how faithfully each model fits to the segmentation. Different models are tested; in this work we expose only one brain model due to lack of space, however similar observation can be done for other models.

Fig. 2 presents the results of the distance measure on the brain model for each of the four reconstruction methods. On the left side, while examining each of the four reconstructed models, one can notice a predominant green color (distance around the voxel size of 1mm) for the FE, DMC and MPU methods. One can notice also that the blue (very small distances) and red (very large distances) areas are much less dominant and not positioned at all at the same place when moving from one model to another. As for CI the results are quite different since a predominance of a cyan color (distance less than half voxel size) and red (greater than voxel size) is observed. Results can be deepen while looking to the curves at the right side of Fig. 2 that shows the distance versus the cumulated percentage of points. Concerning FE and MPU, most points are around the voxel size (FE: 85.52%, MPU: 78, 48%), followed by DMC with 72.08%. As for CI, only 51.16% of its points are around the voxel size. However if we consider smaller distances less that half a voxel size, CI has the greater percentage of points 40% compared to around

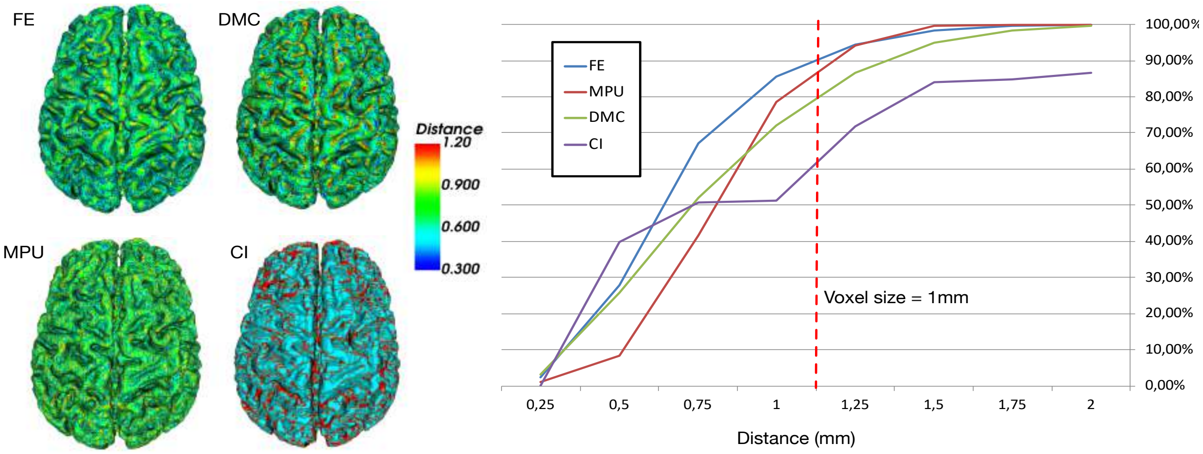

Fig. 2: Visualization of the distance between segmentation and 3D model. The voxel size of the segmentation grid is of 1mm: (left) distance computed with hausdorff metric (blue reflect low distances and red high distances. (right) cumulative percentage of the proportion of element as a function of their distance to the segmentation.

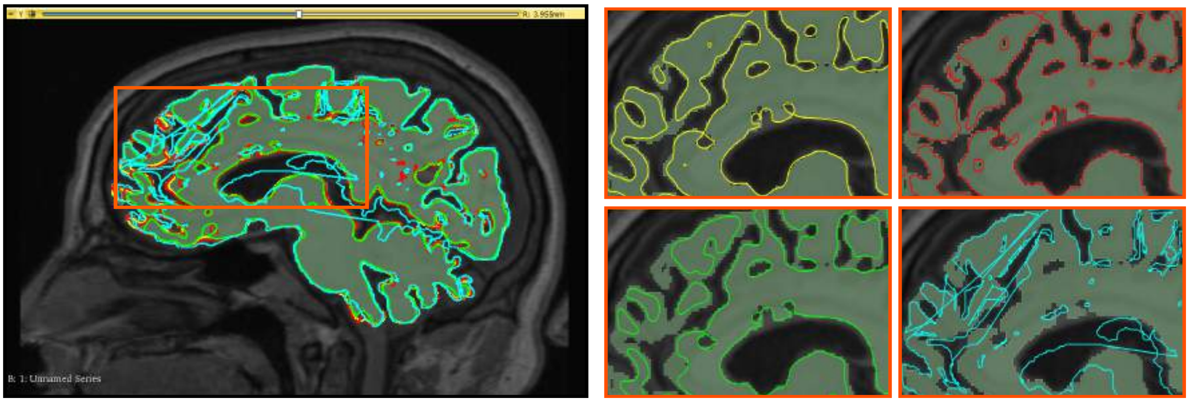

Fig. 3: Reconstruction of the brain with FE (yellow), MPU (red), DMC (green) and CI (cyan); (left) overlaid models; (right) reconstruction result of each method.

30% for FE and DMC and less than 10% for MPU.

Fig. 3 shows a cross section of the four reconstruction method, in the left part all the four models are superimposed with different colors to see them together. On the right part, a zoom on a specific zone (red square) is performed in order to examine the reconstruction details. Once can observe a variation in the reconstruction results like for example some segmented areas that are not always reconstructed, or some deviation on the desired area, or some areas wrongly reconstructed. This reflects the difference on the behavior of each of the reconstruction method.

Discussion:

By comparing the reconstruction results and according to our experiments, we concluded that each reconstruction method has its own disadvantages. MC based methods can produce topologically different results, which are not necessarily consistent with the geometric of the segmentation. In addition, the relevant surface-segmentation distances might get changed because of the smoothing preprocessing applied on the output models. The problems of CI occur essentially where the contours are not similar in shape and size, as well as in the presence of multiple inner contours which is generally the case with intricate geometries like the brain. These cases often incorrectly alter the correspondence between contours and thus triangulate between the inappropriate contours. The major difficulty of the MPU is the integration in the tolerance parameter of both the smoothness and accuracy of reconstruction. To achieve a high level of smoothness, a relatively large value of the tolerance has to be used, which will subsequently result in a poor approximation of the segmentation.

The comparative study examined in this work shows that the various reconstruction methods produce very different 3D models. These variations are due to the fact that the methods are more or less consistent with the geometric configurations of the segmentation.

One of the possible extensions of this work would be to include Magnetic Resonance Spectroscopy and metabolite quantification to improve the 3D reconstructed models. The final purpose is to have a precise 3D model that meet medical expectations and that can be used for diagnosis and virtual biopsy.

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