VOLUME SIMPLIFICATION AND SEGMENTATION BY 3D CONNECTED OPERATORS

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ABSTRACT

An extension to connected operator filtering is proposed here for 3D still images (e.g. biomedical volumes). The "surface preservation" property of this kind of morphological processing can be exploited to obtain a "simplification" effect on the data, deriving from the cancellation of some undesired 3D structures; this is achieved by some filtering criteria which can be related to different objectives, varying from denoising to real structure removal purposes. We also show how the simplification process constitutes a useful pre-processing step to improve the performance of an automatic and/or assisted morphological segmentation of volumetric objects in the case of noisy, natural and complex data, such as MR and CT volumes.

1 Introduction

In general, morphological image processing and analysis tools are very attractive because of their natural ability to deal with shapes and contours of the objects present in visual data. In particular, the use of connected operators [1] has became very popular in the multimedia scenario, both for image [2] and video [3] analysis; this is mainly due to their capability of simplifying the data while preserving the contours, and secondly to their generality and versatility in their formalization and application fields [4, 5]. A unexplored field in connected operation processing is their use on 3D data sets, such as for example, biomedical Magnetic Resonance (MR) or Computed Tomography (CT) volumes. We derive 3D connected operators by a simple extension of well known 2D ones (Sec.2). The simplification effect is introduced in 3D, compared to a repeated single slice filtering and studied in their interesting peculiarities (Sec.3). We continue our contribution by observing, on experimental basis, how the 3D simplification assumes an important pre-processing role in a 3D assisted segmentation system (Sec.4) for biomedical volumes.

2 Connected operators on volumes

2.1 Connected operators for image simplification

Morphological filtering of gray level images by connected operators requires a structured decomposition of an image made of flat zones [1]. By an adequate selection of image features it can provide a simplified version of an image while preserving the information about its contours, as shown in [4]. Connected operators interacts with the signal by means of connected components (in the case of a binary image), or flat zones (in the case of a gray level image): such structures are totally removed (simplification effect), or perfectly preserved (contour preservation), according to some established criteria [4, 5]. We briefly recall the essentials of connected operators filtering. The original image f works as an input for the gray level connected operator Φ. First a thresholding decomposition generates a binary image X_λ for each possible gray level λ (with pixels set to 0 if $f \geq \lambda$); then every binary image is processed by a binary connected operator ψ. Considering every binary connected operator ψ, an *analysis step* assesses the specific characteristic of every connected component, following some given criteria; then a *decision step* states whether or not the connected components have to be preserved (e.g. the component is removed if its size is smaller than a certain threshold). Finally a *staking process* ensures the reconstruction of the gray level image g originated from the set of binary images X_λ, as

$$g = \Phi(f) = \bigvee_{\lambda} (\psi(X_\lambda)) \tag{1}$$

With this rule, the connected operator Φ, produces a filtered image g in which bright connected components are removed following the analysis criteria and the max gray level value on the stack is used to replace them. In a similar way, a dual gray level connected operator Φ' can be defined and implemented to remove dark connected components. As a result, a typical noisy and natural image f can be "simplified" in $s = \Phi'(\Phi(f))$ by eliminating, for example, too small and/or complex connected components.

2.2 3D connected operators

3D connected operators have not yet been studied, nor their application field explored. The extension idea is simple, but implementation, implication and usage are not as trivial.

As for the 2D case, the 3D connected component or flat zones are detected on the basis of a connectivity analysis that, for a three dimensional voxel collection, it is related to the following definition of *local neighborhood system* [6]:

Definition 1 (3D neighborhood system) *Given a 3D finite voxel set* V*, of dimension* $N_1 \times N_2 \times N_3$*, where* $V = \{(i,j,k) | 1 \le i \le N_1, 1 \le j \le N_2, 1 \le k \le N_3\}$*, the 3D neighborhood system* $3D - \eta = \{3D - \eta_{ijk} | (i,j,k) \in V\}$ *is defined where* $3D - \eta_{ijk}$*, that is the neighborhood of the voxel* (i,j,k)*, is such that* $(i,j,k) \notin 3D - \eta_{ijk}$ *and* $(l,m,n) \in 3D - \eta_{ijk}$*, imply* $(i,j,k) \in 3D - \eta_{lmn}$.

Typical neighborhood system that can be adopted are $3D - \eta^1$, $3D - \eta^2$, $3D - \eta^3$, where $3D - \eta^1$ denotes a first order neighborhood system which includes the 6 nearest voxels with respect to the central one; $3D - \eta^2$ is the second order neighborhood system which includes the 18 nearest voxels, and $3D - \eta^3$ includes the 26 nearest voxels. Fig.1 shows the most common choice. In our work we adopt mostly $3D - \eta^1$. The connectivity analysis on 3D flat zones leads to a connected component partitioning on each gray level λ. Undesired connected components can be eliminated by the following filtering criteria selected for analysis-decision process:

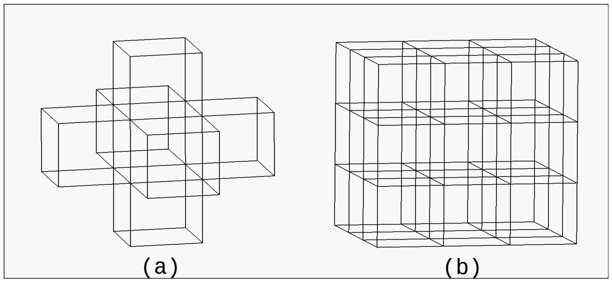


Figure 1: Typical neighborhood systems for the 3D case: a) $3D - \eta^1$; b) $3D - \eta^3$.

- *Opening by a volume measure*: this filter preserves, at the gray level λ, the k-th volumetric connected component C_λ^k if its number of voxel is greater than a threshold v_λ. This kind of criteria simplifies the volume in a size-oriented basis. The term "opening" is related to the fundamental properties of algebraic openings [7] that is: monotonically increasing, antiextensive and idempotent.
- *Volume complexity criterion*: the connected operator removes complex 3D voxel sets, and complexity is measured as the surface to volume ratio $Cmplx_{3D}(C_\lambda^k) = s(C_\lambda^k)/v(C_\lambda^k)$. In fact, similarly to the perimeter to area ratio defined for 2D components, a high $Cmplx_{3D}$ value can be associated to "indented" objects.

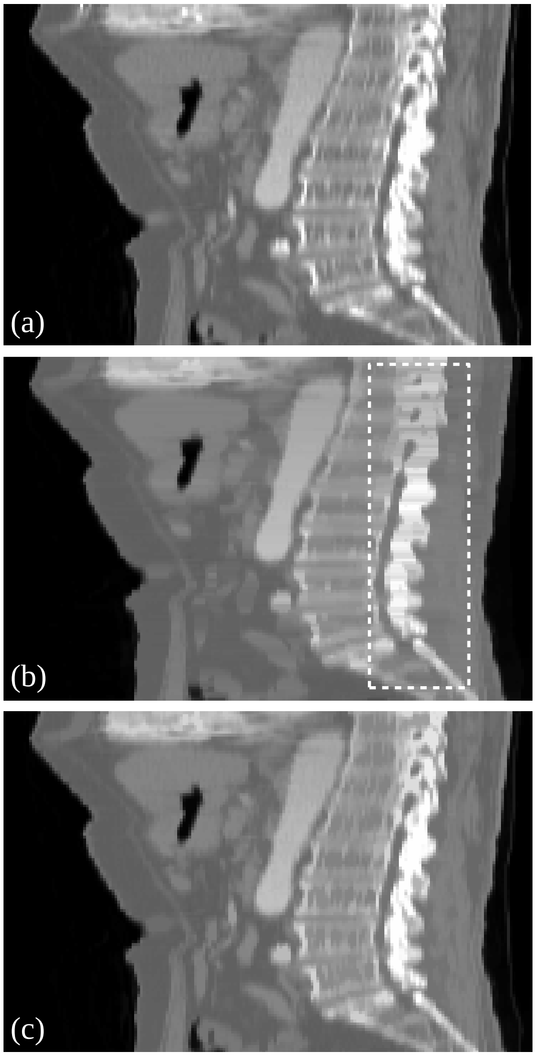


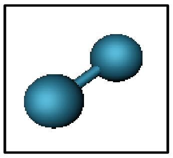
Figure 2: a) Slice from original volume; b) 2D repeated simplification made on the orthogonal planes; c) Direct 3D simplification.

The complexity criterion leads to connected operators which are idempotent, antiextensive but non-increasing [5]. This can be seen observing that even if $C_\lambda^k \subseteq C_\lambda^j$ no a-priori relationship exists between their complexities. Thus, if we consider the stack built on each filtered gray level flat zone, the presence of a filtered connected component at the gray level λ does not guarantee the presence of a more extended one at the level $\lambda^{'} < \lambda$. The use of the *reconstruction by max* law (1) thus can be supported as it guarantees a good contrast preservation of the simplified volume [4]. As we have seen, the 3D extension of a gray level connected operator is straightforward and allows to obtain simpler volumes in terms of small and/or complex bright structures which are removed from the original volume. As a rule, a dual gray level connected operator has to be defined and applied for dark structure filtering.

With respect to a 2D approach, the volume simplification by 3D connected operators involves some additional computational costs due to the topological degrees of freedom during the filling of the connected components, given a certain neighborhood system. A possible alternative to the direct volumetric approach can be implemented by repeating two-dimensional simplifications on each image, taken from a sliced decomposition of the volume, followed by the volume recomposition. In the next section this alternative is considered and the different results compared in order to justify the need of the direct 3D approach.

3 Direct volumetric simplification

As anticipated, with the direct approach each connected component C_λ^k of the flat volumetric zone V_λ of the volume V is detected (by an efficient *flooding* algorithm), and labeled with a number k. Then, surface $s(C_\lambda^k)$ and volume $v(C_\lambda^k)$ are calculated (actually these estimates are issued from the above algorithm). At this point, the connected binary operator Ψ works on V_λ by analyzing the selected 3D characteristic and deciding on them. This procedure and consequently the following stacking (1), may lead to strongly different results if compared to a repeated 2D filtering (with respect to any slicing direction), even if the analysis and decision criteria are scaled and kept in strict correspondence.



This fact can be easily understood considering the nearby structure. Suppose that this structure is preserved by an opening by volume or 3D complexity basis. In a repeated 2D framework, some 2D sections may be discarded, part of the structure split and modified. In addition, the result strongly depends on the slicing direction too. In Fig.2 a body CT volume is considered as a real case, where the images have been obtained by re-slicing the volume orthogonally with respect to the 2D filtering plane. Many *stripping* or structure deformation artifacts occur on the volume processed by 2D repeated filtering. The result appears useless for any segmentation purposes, because of the impairment of the volumetric connected components. In the example of Fig.2 the surface and volume thresholds for the 2D and 3D openings were respectively set to $s_\lambda = 30$ and $v_\lambda = 1000$.

A simplification result is shown in Fig.3, using a opening by volume criterion with $v_\lambda = 1000$ voxels, for all λ. The perspective view has been obtained by direct volume rendering of a portion of the head-MR 3D dataset dissected by using 2 orthogonal cutting plane. There is a good coherence between the simplified volume and the original. Obviously this kind of filtering is critical, especially on diagnostic medical data; thus the potential utility has to be considered in a real application context.

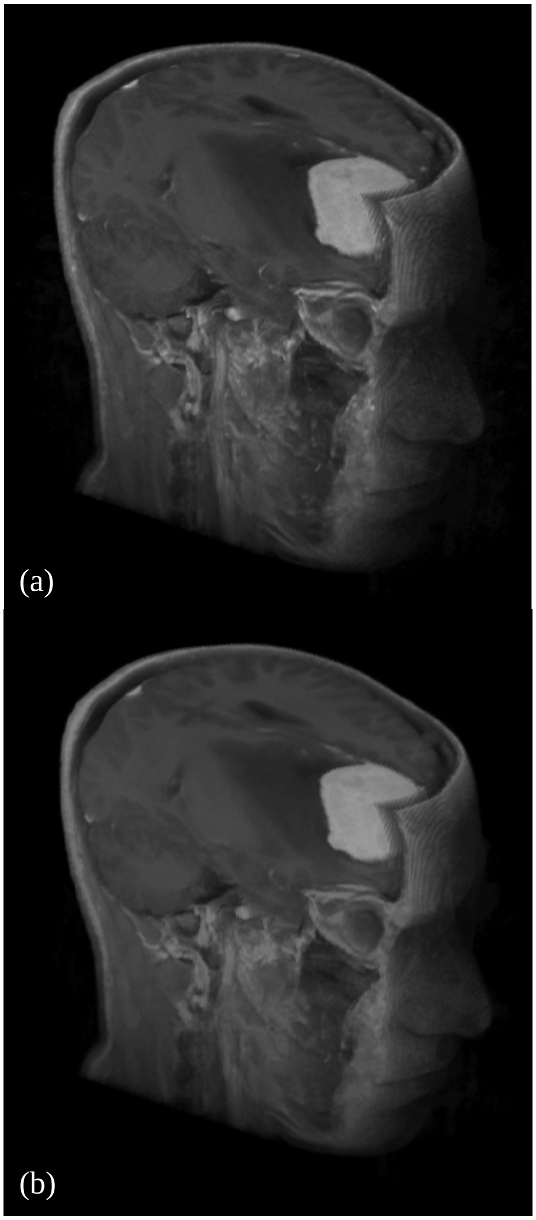


Figure 3: a) Original head-MR volume b) and the corresponding simplified one.

4 An application scenario: diagnostic segmentation and visualization

In this section we want to briefly discuss the role and the usefulness of the 3D simplification as a pre-processing stage in the segmentation of diagnostically relevant structures and their subsequent visualization in a clinical evaluation scenario. Medical images and volumes are noisy by nature, and from a morphological point of view noise can be revealed by the filter "granularity". It can be easily observed that on two-dimensional volume slices (images), noise and dissected structures have an interpretation misleading potential which can be greatly reduced in a 3D workspace; this is because 3D noise remains granular, while structures shows their actual anatomic nature (shape). In general, denoising is useful before segmentation if the processing does not destroy the information which is necessary to accomplish the segmentation task. In this sense, we experimentally observed that there is a favorable condition for the use of 3D connected operator denoising of biomedical volumes with an opening by volume filtering criterion. In Fig.4 we show some successful segmentation and visualization results on relevant diagnostic structures. The images have been obtained with a morphological based system for the assisted segmentation [8] and visualization of diagnostic images. In Fig.4(a) a brain meningioma has been segmented by a neuroradiologist in 1'30" interaction time. The structure shows a determinant diagnostic value, namely the dura mater tail, indicated by the arrow. This fine tail has been preserved by the 3D simplification, but would have been completely destroyed by the 2D repeated one. The pathology is also shown in its context by the segmentation of the brain, in slight transparency. In Fig.4(b) the gray matter of a MR brain volume has been extracted by the physician during a 7' long interaction (the manual segmentation time is about 4 hours long). This accurate and diagnostically useful result cannot be obtained by the same system without the simplification pre-processing, due to the noisy and complex nature of the original data. The same indented brain structure is shown in its context after others interactive steps which adds the skull and the head skin in transparency. Therefore, thinking of the segmentation task as subdivided in general criteria (denoising, structure simplification) and specific strategy (automatic or assisted morphological segmentation), we have observed that simplified volumes seem to be a good starting point for a subsequent segmentation, allowing the algorithm to became more effective.

5 Conclusions

In this work a simple 3D extension of connected operators has been introduced. Filtering criteria and peculiarities of a direct 3D processing have been discussed in order to justify the usefulness of the volumetric approach, despite the related computational cost. The 3D simplification effect has been studied and, on experimental bases, it has been shown how the properties of simplified volumes, where most of the complex and small structures (noise), can help a subsequent segmentation task. In fact, with a proper choice of the filtering criteria the presence of important anatomical and pathological structures is totally preserved and revealed.

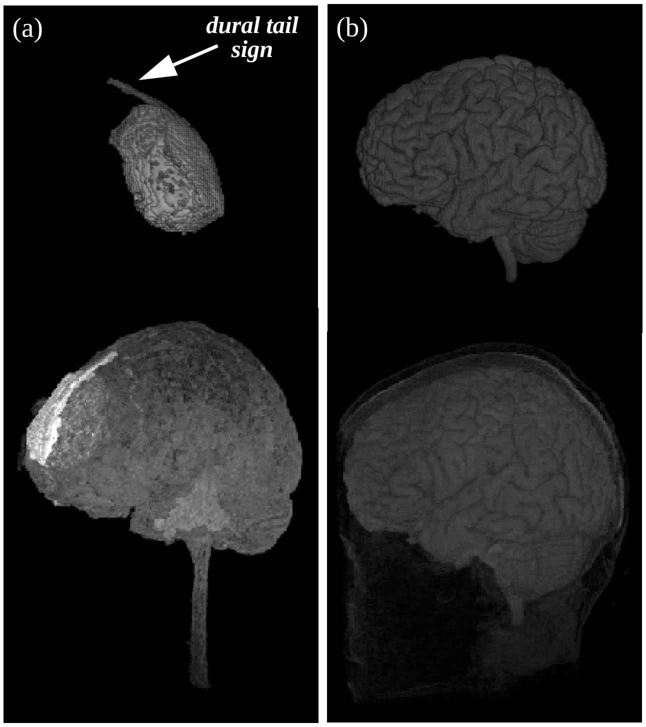


Figure 4: Segmentation and visualization results.

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