From 3D soil Computed Tomography images to geometrical soil structures
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Abstract

Since less than one decade geoscientists started to use 3D soil tomography images in order to achieve better understanding and modeling of soil properties. In this paper we propose one of the first approach for defining and computing stable (intrinsic) geometrical representations of structures in 3D tomography soil images. This task sets the still open problem of describing volume shapes from discrete traces without any a priori information. Our basic idea is to describe the corresponding volume using a set of patches of volume primitives (bowls, cylinders, cones...). The volume primitives representation is assumed to optimize a criterion ensuring its stability and including a characterization of its scale (trade-off : fitting errors/number of patches). Our criterion takes also into account the preservation of topological properties of the initial shape representation (number of connected components, adjacency relationships...). We propose an efficient computing way to optimize this criterion using Delaunay triangulation in an initial stage and optimal region growing in a final stage. Region growing is performed on the adjacency valuated graph representing the primitives and their adjacency relationships. Our method is applied to the modelling of porous media from 3D soil images. This new geometrical and topological representation of the pore network can be used to characterize soil properties.

Keywords : 3D soil tomography images, Computed Tomography, soil images, functionnal minimization, soil properties, geometrical modeling

Résumé

Depuis une dizaine d'années, les chercheurs en Sciences du sol ont commencé à utiliser l'imagerie tomographique tridimensionnelle. Dans cet article, nous proposons une des premières approches permettant de définir et de calculer des représentations géométriques stables et intrinsèques de structures du sol à partir d images tomographiques 3D. Cette tache pose le problème toujours ouvert de décrire des formes volumiques à partir de traces discrète sans information à priori. L'idée de base consiste à décrire la forme par un ensemble de primitives volumiques simples (boules, cylindres, cônes). Cette approximation par morceaux est supposée optimiser une fonctionnelle qui assure sa stabilité et inclut une caractérisation de son échelle (compromis : erreur d'approximation / compacité de la représentation). Nous prenons aussi en compte la préservation des propriétés topologiques de la forme initiale (relations d'adjacences, nombre de composantes connexes...).

Nous proposons une méthode efficace pour optimiser ce critère en utilisant la triangulation de Delaunay dans l'étape initiale et ensuite la croissance de région optimale. Nous appliquons notre méthode à la modélisation de l'espace poral obtenu à partir d'images volumiques 3D du sol.

Mots clés :

Images tomographiques 3D du sol, minimisation de fonctionnelles, modélisation géométrique, triangulation de Delaunay, croisssance de régions.

1 Introduction

This article deals with the generic problem set by the definition and the computation of stable (intrinsic) representation of volume shapes from discrete traces. This question is a key point for various application fields such as : soil science, medicine,... where tomography allows to get 3D volume images describing structural and topological information. In this paper we present an innovative method to provide stable representation of a discrete volume shape into a set of volume primitives (bowls, cylinders, cones...) without any a priori information. Our approach adapts classical segmentation algorithms to the specific problem set by 3D volume shapes segmentation [Schmitt, 1994] [Faugeras, 1984]. The discrete volume shape is assumed to be defined by a 3D image where all points of the shape are marked that is set to one.We apply our method to the geometrical modelling of pore space in 3D soil tomography images. The pore space corresponds in soil data to empty or free space in the sense that no material is present there but only fluids (air, water, gas,...). We propose to approximate pore space using cylinders that can be interesting for soil properties in some specific cases (earthworm burrows characterization for instance). We stress that the computation of cylinders piecewise approximation is only an example illustrating a practical implementation of this approach which can be used for many other geometrical primitives eventually mixed. We present experimental results on real data. A segmentation problem can be specified by the nature of its input and also the desired output. In the case of 3D soil tomography image, initial data is a set of voxels defining a completely whatever volume shape (for instance the poral space -empty space-) without any a priori information about its geometrical nature. Moreover, we do not use any interactive tools to guide the process like in many modeler based approaches. The desired output is a set of primitive volume shapes (bowls, cylinders, cones. . .) defining a piecewise approximation of the initial shape. This piecewise approximation should be intrinsic i.e. depends only on the initial shape and not for instance on the way data are processed. Moreover, the piecewise approximation should be defined by a scale factor characterizing the trade-off between the fitting error and the compacity which is related to the number of pieces of the final representation. If we go through the literature about 3D shape segmentation, one does not find many papers dealing with our specific segmentation problem. Level set based approaches consist in the propagation starting from an initial position of a closed surface towards desired boundaries [level set 2]. This is realized thanks to the evolution of a 4D implicit function. In order to apply this method to our data we should give also interactively as input initial positions. Moreover, the result is a representation of the shape using implicit functions which is different from a piecewise approximation. Indeed, the implicit function based representation is valuable due to its compacity and also to its analytical nature. But it does not define an intrinsic representation of the shape because depending strongly on the initial conditions and on the propagation scheme. However, this representation can be used for many purposes (visualization,. . .) because much more easy to manipulate than several million of voxels. But for our specific data, we need a representation from which can be directly derived significant shapes linked to soil properties (cavities, galleries,. . . .).Dynamic 3D models using deformable superquadrics [Terzopoulos] follows almost the same specifications than level set based methods. Superquadrics is a flexible family of 3-dimensional parametric object useful for geometric modeling. By adjusting a relatively few number of parameters a large variety of shapes may be obtained. A particularly attractive feature of superquadrics is their simple mathematical representation. Once again, this representation is very adapted to visualization and storing purposes but much more less for defining intrinsic and stable shape representations. Metaballs based methods use a generalized definition of spheres using weight and fusion degree [Blinn]. It yields to represent complex shapes using parts of bowls. May be, we could use this kind of approach in a second stage starting from a recovering of the shape by a minimal number of Delaunay spheres including the skeleton.Within the context of geological applications, many methods have been developed in "GOCAD" project [Caumon 2]. Once again the goal of these method is to represent geometrical information in a compact and manipulable way which is valuable and important, more than in an intrinsic and stable manner.

2 Algorithm scheme

Our initial data is a 3D image $I(x, y, z)$ where all points of the volume shape is set to one. The main stages of our algorithm are :

- Computation of the envelope of the volume shape. This surface can be provided by straighforward algorithms and also using marching cubes methods [Lorensen, 1987].

- Computation of 3D Delaunay triangulation of the envelope points. We use an algorithm developed by GAMMA project at INRIA [George, 2004] [George, 1998] [medit].

- Pruning of Delaunay triangulation by removing the tetrahedra not included within the volume shape. This stage is easy because in this specific case we have a complete discrete description of volume shape. Therefore heuristics developped in [Faugeras, 1984] can be avoided.

- Computation of the skeleton of the shape volume using Delaunay triangulation. We approximate the skeleton by the centers of Delaunay spheres [Schmitt, 1994].

- Computation of an initial piecewise volume representation of the shape using the skeleton, Delaunay spheres, and Delaunay triangulation. We can approximate the shape using bowls or using thin cylinders ("sausage slices").

- Merging of the volume primitives of the initial piecewise representation using optimal region growing [Lorensen, 1987]. We define a criterion evaluating the quality of the 3D segmentation by adding the fitting error and a scale factor multiplied by the sum of the areas of the primitives. The two parts of the criterion (fitting error and compacity) are of course antagonist and the scale factor λ defines the trade-off. This last stage provide a piecewise approximation of the shape using an "optimal set" of volume primitives (cylinders, cones..).

Figures 1 and 2 present some experimental results on real data describing the main stages of our method. Figure 1 and 2 shows up to down and left to right :

- 2 perspective views of the poral space extracted from a 3D Computed tomograhy image of macro-porous sandy lime soil

- 2 perspective views of 3D Delaunay triangulation of the volume envelope corresponding to previews views

- 2 perspective views of the result of Delaunay triangulation pruning

- 2 perspective views of "maximal Delaunay spheres" ; we put iteratively the Delaunay bowl whose radius is maximal and who do not intersect the already selected bowls.

- 2 perspective views of thin cylinders.

- 2 perspective views of the final approximation using cylinders

- 2 graphics presenting the relationships between the scale factor, the fitting error and the number of cylinders (first graphics : X axis : scale, Y axis : number of cylinders ; second graphics : X axis : scale, Y axis : fitting error).

- 2 perspective views of the poral space extracted from a 3D Computed Tomography image of a sour lime soil data

- 2 perspective views of the final approximation using cylinders

3 Conclusion

In this article, we present an innovative method for modelling geometrical structures in 3D soil tomography images. Our approach is based on the scheme : Delaunay triangulation of the borders, selection of initial primitives using Delaunay spheres, merging initial primitives using optimal region growing. It can be adapted to compute various geometrical shapes representations. We are currently working in order to find out a practical way for defining and computing typologies of the coarse pore space using mixed geometrical primitives. The aim is to propose geometrical typologies which can be linked to soil genetic and functional interpretation. Many thanks are due to Paul Louis GEORGE head of GAMMA project at INRIA Rocquencourt for having put to my disposal his 3D Delaunay triangulation algorithm. Indeed, the quality of Delaunay triangulation which is applied to huge number of points (up to several millions) is a key point to get good experimental results. Thank you very much also to Jean Pierre TREUIL for fruitful discussions about this paper and to Jean François DELERUE for having put to my disposal soil data. Thank you also to Guenola PERES for having put her data to my disposal.

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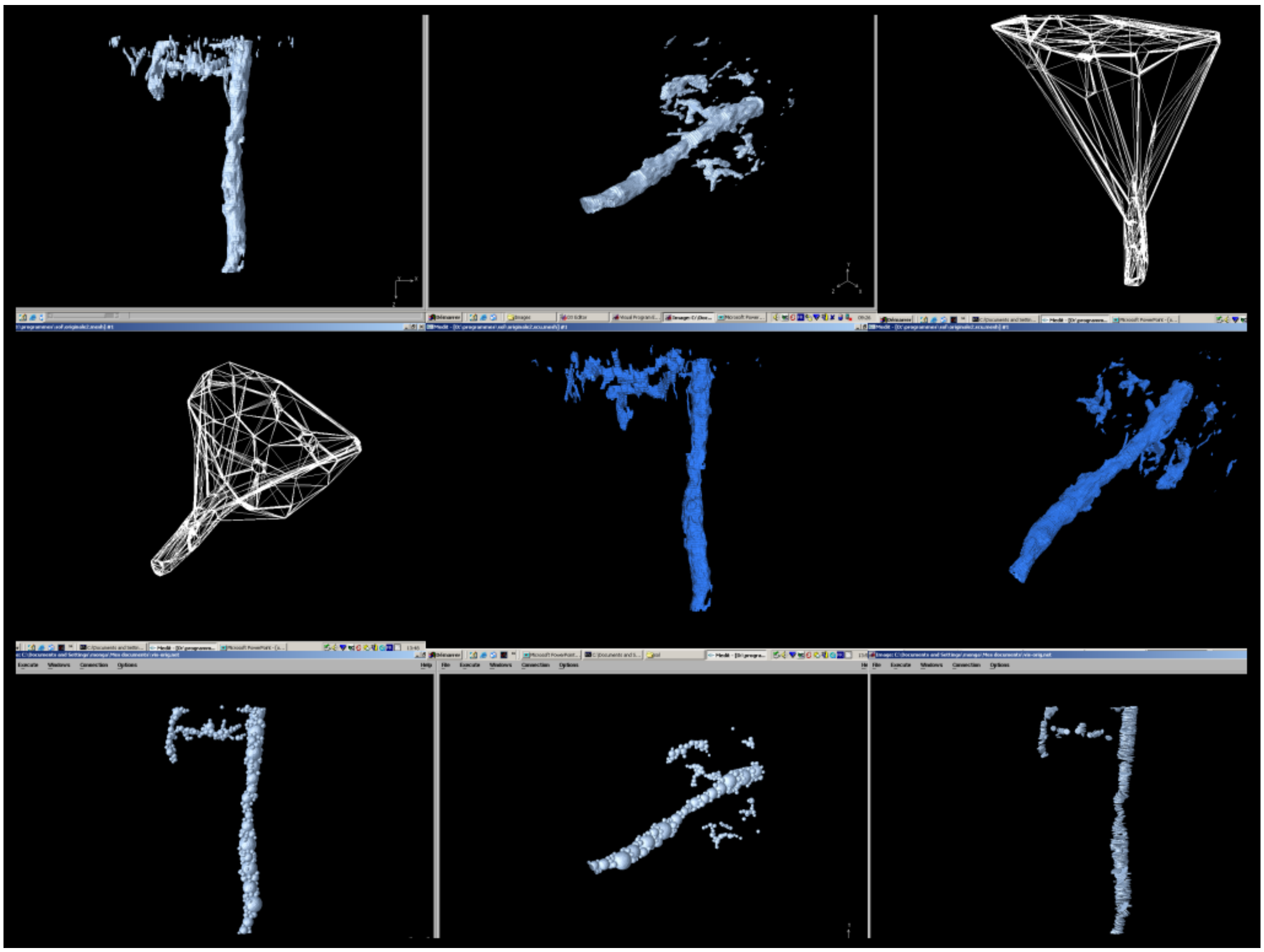

Figure 1: From initial data (macro-porous sandy loam soil) to thin cylinders (sausage slices)

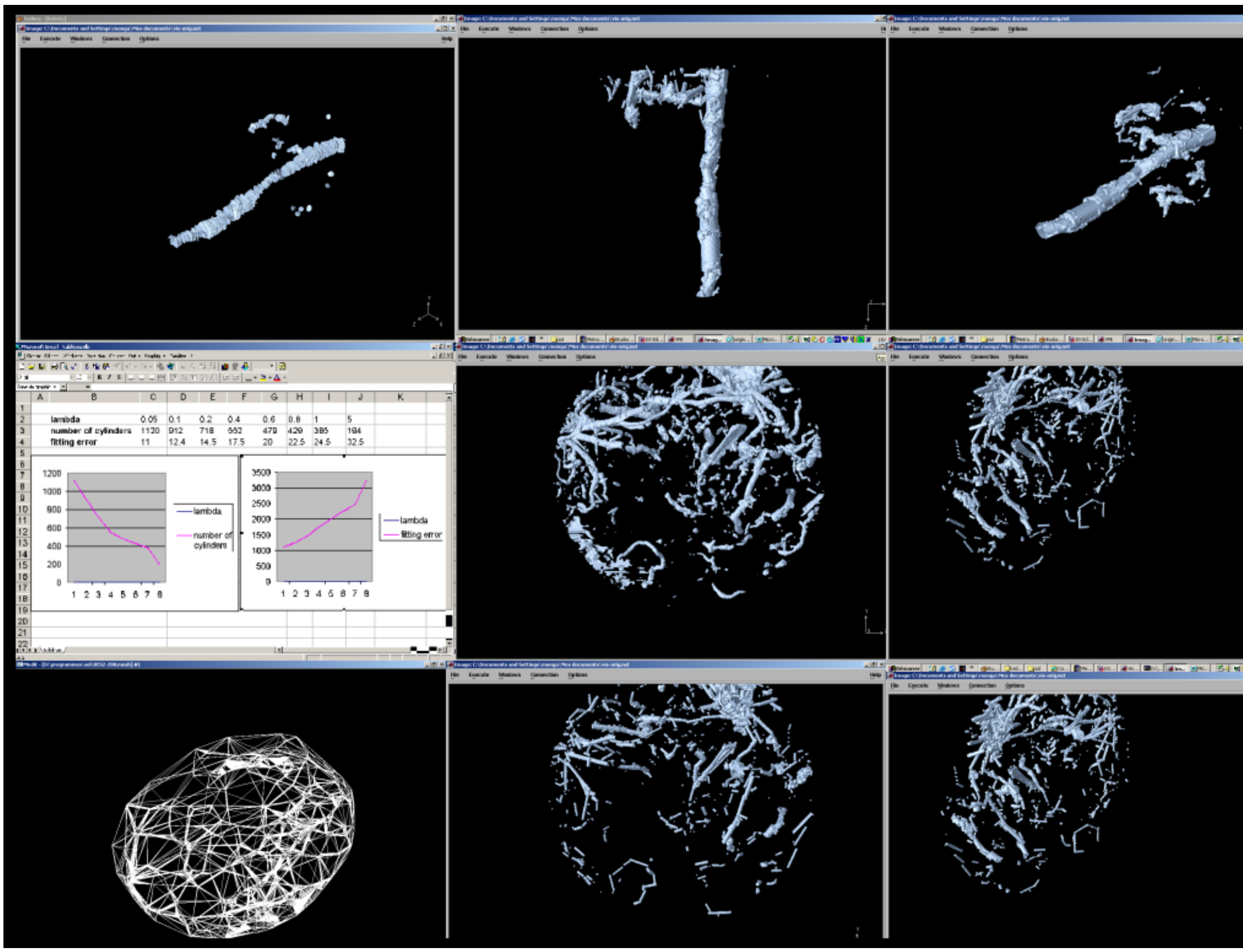

Figure 2: From thin cylinders to cylinders, statistics about scale, sour lime soil data