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## Research Trends in Volume Modeling

Isabel Navazo

Anna Puig

Dani Tost

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Facultat d'Informàtica  
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## **Abstract**

Volume modeling has recently emerged as a promising field of research and development. A generic scheme of volume modeling applications is proposed and applied to existing volume modeling applications. Next, volume modeling is analysed at three levels: physical model, mathematical model and representation schemes. A medical application is studied in order to illustrate these three levels of abstraction. The future research trends in volume modeling are next summarized.

# Research Trends in Volume Modeling

I. Navazo, A. Puig, D. Tost

## 1.- Generic scheme for volume modeling applications

### 1.1.- Introduction to volume modeling.

Classical representation schemes for solids are restricted to the modelization of the shape of their external surface. The internal volume is assumed to be filled with an homogeneous and isotropic material. However, the increasing development of new fields of CAD application such as molecular systems, medicine or geology systems, requires the codification of both surface and volume information in the object representation.

Volume modeling is aimed at defining a mathematical model able to represent accurately the internal properties of an object and at investigating computational representation schemes of this mathematical model. This process is represented in figure 1. It should be noted that it is similar to the surface modeling scheme [Req80] in which the mathematical model is aimed at representing the properties of the surface of the objects.

In fact, volume modeling must codify not only the properties of the volume of an object but also, if necessary, the properties of its surface. In this sense, volume models include geometric surface models, because they deal with 3-dimensional information whereas surface models are bi-dimensional. Thus, volume models can be considered as hybrid models, that is, surface models and volumetric models.

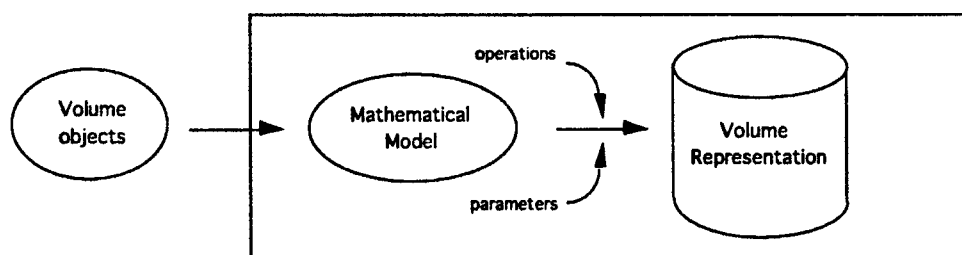


Figure 1: Three-level view of volume modeling

In the next sections of this report, we analyse each of the three levels of volume modeling: the physical model in section 2, the mathematical model in section 3 and the representations in section 4.

### 1.2.- Specification of volume modeling systems.

In figure 2 a generic scheme of a volume modeling system is represented. It consists mainly of four functional modules:

- the input module, that constructs a general model of the volume from the original data. This model is called general because it codifies the whole information at the maximum level of precision. However, it should be noted that general model is specific to each application.
- the evaluator, that constructs a specific volume model from the general model, according to several parameters. These parameters are related, among others, to the properties of the volume data, to the level of approximation of the representation that is required in the application and to conciseness of the representation.
- the operations module, consisting of visualizations, volumetric computations, selection, simulations. Because volume models are inherently hybrid, their operations can be extended to mixed scenes composed of geometric surface models and volume models [TPN93].
- the conversor, that computes other specific representation schemes from the original one, in order to perform some operations more accurately.

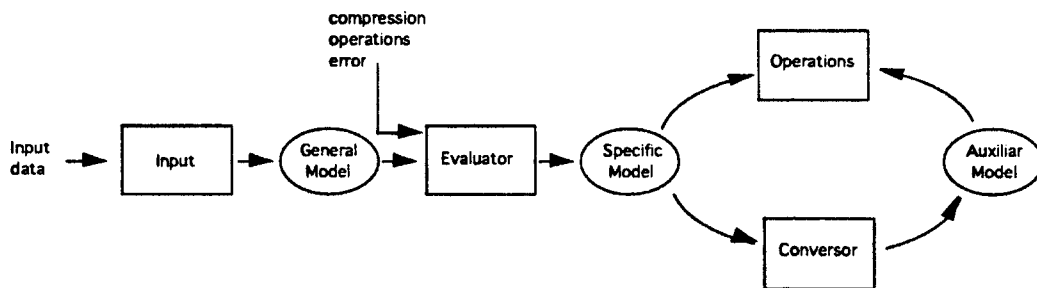


Figure 2: A general scheme of a volume modeling system

### 1.3.-Volume modeling systems based on spatial enumeration representations.

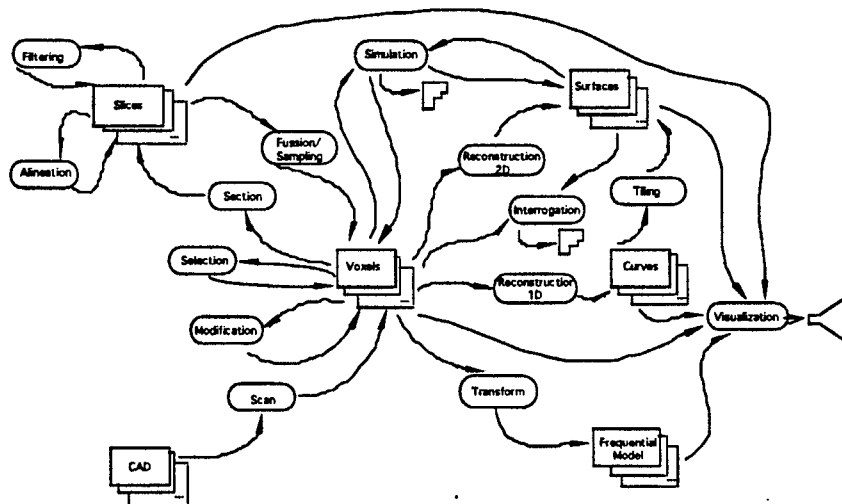


Figure 3: A scheme of a voxel-based volume modeling system

Current volume modeling systems are based on a unique specific representation scheme: the spatial enumeration rep (voxel model) [Kau91] constructed directly from the input. Up to now no general representation scheme has been proposed. In figure 3, the generic scheme presented in figure 2 has been applied to the voxel model and the operations have been detailed according to the conclusions of a bibliographical study [PNT93].

## **2.- Physical model**

### **2.1.- Volumetric objects typification**

Potentially, all physical objects can be represented in volume modeling systems, but currently the represented objects proceed mainly from the following fields of applications: medicine, geology, biochemistry, chemistry and fluids mechanic.

A criterion of classification of these physical objects is their *homogeneity*, defined as the number of connected areas in the objects that have properties values inside specific ranges. A second criterion is their *linearity*, defined as the variation between the properties values of neighbouring points within homogeneous areas.

### **2.2.- Characteristics of sample data.**

The data from which the volume representations are constructed generally arise from numerical simulations and from scientific measurements. They consist of a set of points with a collection of associated values (parameters), measuring specific properties at the given spatial location. The main characteristics of the data are [PTN93]: the number of sampled points, the dimension of the nets of points, the type of nets, the number of parameters per point, the parameters type and the dimension of the parameters.

The number of sampled points that is necessary in order to construct a volume representation at a given accuracy and precision depends on their linearity.

## **3.- Mathematical model**

### **3.1.- Point Topology**

Most of the bibliography [Kau93] is centered on representation schemes for volumetric objects, but very little has been written about their mathematical models [Nie93]. From the analysis of the characteristics of the physical volumetric objects, it is clear that the most general mathematical abstraction is the set of all their points with their associated properties values. This naturally leads to the point set topology model [BJN93]. However, as pointed in [Man88] this model is far too general and may represent a too large class of objects. The characteristics of volumetric objects should be taken into account in order to define the properties of a more narrow subset of the point-set topology model: the volumetric-set.

### **3.2.- Volumetric sets**

The properties of volumetric objects that seem most significant in order to define the volumetric-set are the above defined homogeneity and linearity.

The homogeneity allows to define connected areas inside the volumetric objects such

that the values of a given property of all the points of an area vary within a pre-determined range. Thus, it may be possible to define a function, associated to the given property, for each homogeneous area, that defines the value of the property for each point of the area with an error  $\epsilon$  depending, among others, on the selected ranges. As an example, the most simple function would be that one which would associate to each point of an homogeneous area, a constant value within the range, with a maximal error equal to the width of the range.

The volume model could therefore be characterized as a union of all functions of a property, for all the properties:

$$\bigcup_{j \in \text{Prop}} \left( \bigcup_{i \in \text{Areas}} f_{ij}(x,y,z) \right)$$

These volumetric functions may be of different classes: stochastic, parametric, interpolating, of transformed space... A typification of these volumetric functions should be done along with an analysis of their adequacy for representing different volumetric objects. As an example, interpolating functions may be more adequate for modeling objects with a high linearity level, whereas stochastic functions may be suitable for non-linear, textured objects.

## 4.- Representation schemes

### 4.1 Properties

A mathematical model may have different computational representation schemes. These representation schemes may be evaluated according to different criteria [Man88]: their domain, their validity, their unambiguity and uniqueness, their concisness, their computational ease and applicability.

### 4.2 Evaluation of existing volume representation schemes

Currently the Spatial Enumeration rep (voxel model) is the representation scheme most widely used. It is based on a decomposition of the 3D space into a regular set of identical cubical cells, *voxels*, whose edges are parallel to the coordinate axis. This spatial structure allows to directly represent a voxel by a vector  $(i, j, k)$ , where  $1 \leq i, j, k \leq n$ , (being  $n$  the number of voxels per axis), from which the whole geometrical and topological information of the voxel may be retrieved. In addition, each voxel has associated a set of values, either at its center, either at each of its eight corner vertices.

As mentioned before, most of the input data are regular nets of points, thus the construction of the voxel model consists simply in resampling the data. This is one of the reasons of the wide use of this representation. Another advantage is the facility of the operations that can be reduced to voxel level operations.

The two main drawbacks of this representation scheme are:

- that it is an approximate representation: The resolution of the voxel model is assumed to be such that, either the voxels may be considered as uniform in relation to a given property, either the property varies slowly inside the voxels. This hypothesis are related with the above mentioned properties of homogeneity (in both cases) and linearity (in the second case, only) of the mathematical model. Therefore, the values of internal points in a voxel can be computed on the basis of the corner vertices values with an error,  $\epsilon_{rep}$ , depending on the error  $\epsilon$ , of the mathematical model.

— that it lacks of concisness: The storage requirement of a voxel model is

$$n*n*n*\sum_{i=1}^{np} p_i$$

where  $np$  is the number of properties and  $p_i$  the storage requirement of a value of the property  $i$ . In order to solve this problem, different compression and compactation methods must be analised.

Another representation is the octree model: it is a tree that encodes the recursive subdivision of a finite cubic universe. In this structure, each node is a terminal node or has eight descendents. There are different kinds of octree depending on the type of terminal nodes [BJN93]. Octrees have been mainly used for solid representation, but they could be adapted to volume modeling [WiG92]. When the properties of the physical object define extensive enough homogeneous regions, the octree representation is a compactation of the voxel model. In this sense, octree representations may solve the lack of concisness of the voxel model. A comparative study of the adequacy of different octrees for some volume models has been realized [Bru92][BJN93]. It must be generalized and extended.

Transformed space representations, based on the extension to 3D of the image compression techniques, are being analised: specific techniques for visualizing volume models using Fourier transformations have been developed [Lev92][Ma193] and a new representation scheme based on wavelets have been presented [Mur92].

## **5.- A case study of a medical application**

### **5.1 Introduction to medical applications**

Until recently, medical imaging techniques were mainly x-ray projections that allow to visualize internal structures of the human body but do not provide depth clues. New technologies, such as MRI, PET, SPECT or Ultrasound, provide cross-section images of these internal structures. These images can be interpreted directly, however, a 3D reconstruction allows more accurate analysis and diagnostics. The aim of volume modeling in medicine is to provide 3D representation schemes of the anatomic structures and the procedures that operate with them.

Medical applications are based on a process similar to the one represented in Figure 2. The input data (images) are first resampled and filtered, then a volume representation (voxels) is built that allows to perform different operations including the visualization. There is a large variety of algorithms for 3D medical visualization, however their high computational cost prevents their use in real time and, because of their low accuracy, they are still not well accepted by the medical community [Rhod91].

Medical applications of volume modeling and visualization can be roughly classified into three groups: diagnosis, simulation and education. The visualization of the 3D structures from different points of view is specially helpful for the diagnosis of fractures of complex shape bones, such as the collar bone, the elbow, the knee and the pelvic ring, and for the detection of tumors. Examples of simulation of operations are prostheses fitting, and radiology treatment planning.

Some of the most important medical applications are represented in the figure 4. In the next section, a specific medical application is presented and analysed in order to illustrate the concepts presented in this report.

Area of the body	Problem	Types of sections	Utility
Pelvic ring	Very thick and of difficult exploration bones	Axials and coronals	Detection of interruptions, of anterior and posterior diastasis. Location of the fragments of the fractures.
Sacro-iliac	Joints that are difficult to see because they obscure each other and because the intestines occlude them. Specially difficult in old patients with osteoporosis.	2D transaxials and coronals series  Sagittals sections  Oblique sections	Small fractures and subtle diastasis  Exploration of the central channel and detection of pre-sacro bruise and fat masses  Foramines
Acetabulum	Thick and long bone	Transaxials CT  Coronals and sagittals CT	Fractures, interruptions of the spine and displacements  Articulations joints
Knee	Complex bone	Transaxial sections 2D coronal and sagittal reconstructed images	Measurements of the fracture extension.
Ankles	Complex bone	Transaxial sections and utilization of multimodal techniques.	Evolution of bones, soft tissues and ties and their interrelations.
Shoulder	Complex bone with registration problems due to the breathing movements.	3D-reconstruction and spinal and transaxial views.	Dislocations, trauma and axilar masses
Spine	Complex bone	Transaxials and spinal views	Fractures, trauma, oncology, infected etiologies, degeneration.
Liver/ Brain	Material difficult to be detected	Use of CTAP (Computed Tomographic Arterial Portography)	Determination of small de lesions. Detection and location of tumors
Trunk	Total definition of the bronquial tree.	Use of helicoidal CT. 3D reconstruction	Location of tumors. Minimization of the number of incisions . Radiotherapy planning
Muscles and soft tissues	Material difficult to be detected	Transaxials views and 3D reconstruction.	Measurement of the extension of tumors. Relationship of the tumor with the bones and the muscles. Vascularity of the tumor.

Figure 4: Main medical applications

## 5.2 Blood vessels modeling and visualization

The objectives of the application are first to compute the current blood flux in the vessels, in order to detect possible vascular obstructions and next, to simulate the aging process of the vessels, in order to predict future vascular accidents.



There are three input data sets: a stack of MRI slices of the head, a set of points with their associated velocity proceeding from a doppler enregistrement and a statistical model of the vessels aging process that takes into account several parameters of the patient (colesterol level, age, smoking, ...).

A first design for the application leads to the functional scheme represented in the figure 5.

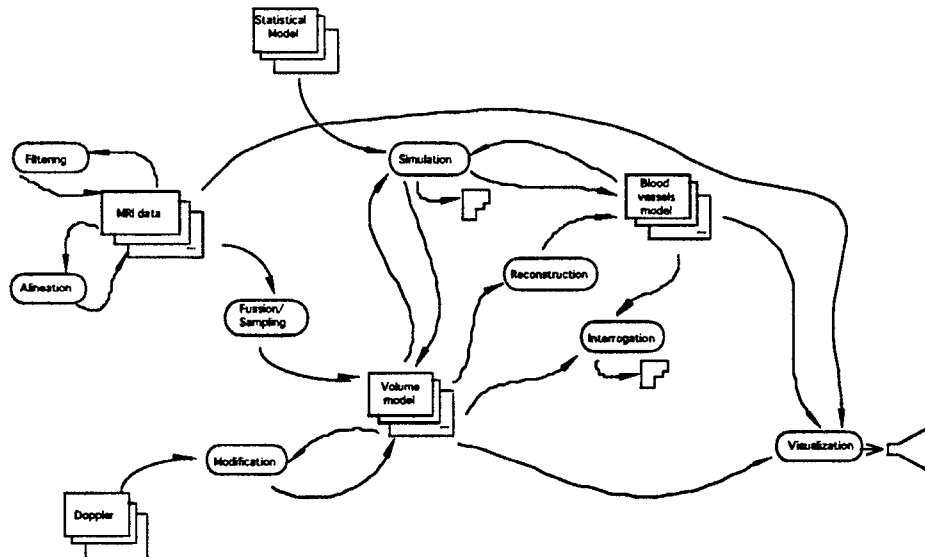


Figure 5: Functional scheme of a medical application.

The volume model is built from the MRI slices and represents the whole volumetric information of the head (blood vessels, brain, bones,...). In the modification process, the velocities, registered with the doppler, are included in the volume model. In order to simulate the blood flux and to predict the future flux, an auxiliar model of the vessels map must be reconstructed from the volume model. The visualizations can be performed in both models for analysing the results of the simulations.

An analysis of the application from of three-level modeling point of view defined previously, may be summarised as follows:

### Physical model:

- *Typification of the objects*: the whole internal structure of the head. This internal structure presents homogeneous areas regarding to the density values that correspond to the brain, the bones and the blood vessels map. The velocity differentiates two homogeneous areas: the non-zero valued area (blood vessels) and the zero valued area (the rest of the head).

- *Sampled data*: regular cubical net of 256x256x60 points with a distance of 1mm from point to point, multivaluated (density, scalar, and velocity, 3D-vectorial).

### Mathematical model:

The volume should be analysed separately for the two properties. The ranges of each property should be computed. For the density there are at least three ranges corresponding to the three main physical structures (bone, vessels and brain). For the velocity there are at least two ranges corresponding to the vessels and to the rest of the head, but a more narrow definition of the ranges could allow to differentiate several

types of vessels. In each area, the linearity level should be computed. Then, the most representative mathematical model should be defined. As the density-homogeneous areas in the head are very linear, it seems that interpolation functions could be the basis of this mathematical model.

#### **Representation model:**

A comparative analysis of different representation models should be done. A possibility could be the voxel representation for the volume model and a surface model of piping for the blood vessels model.

### **6.- Future trends**

In this report, a generic scheme of volume modeling applications have been proposed. Next, the three level view of modeling has been analyzed and illustrated with a medical application. The future research lines in volume modeling are next summarized.

#### *Formalization of mathematical model:*

- Study of point topology model.
- Typification of the modeling functions.
- Analysis of hybrid models.

#### *Representation schemes:*

- Comparative analysis of volume representations (voxels, octrees, transformed spaces) evaluating their adequacy for the proposed mathematical models.
- Proposal of new volume representations allowing different levels of precision and compression.
- Proposal of hybrid volume representations schemes.

#### *Operations :*

- Functional specification and design of algorithms of visualization, volumetric computations and deformations suitable for the proposed representation scheme.
- Functional specification and design of algorithms of conversion between representation schemes.

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