AN INTEGRATED AND EFFICIENT VOXEL-BASED RENDERING SYSTEM : FROM DISCRETE SKELETON SHAPE DESCRIPTOR TO IMPLICIT SURFACE VISUALIZATION

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ABSTRACT

This paper presents a new algorithm of volume rendering based on a dual representation of data in order to improve at the same time the image generation speed and its quality. Two shapes descriptors are used then to characterize the object : an Euclidean Distance Transform (EDT) and a digital Euclidean skeleton. The EDT is used at a time to accelerate the image generation and compute the skeleton of this shape, whereas skeleton is used as an initialization to the processing of the implicit surface. The goal consists in the obtaining of an interactive system of visualization for the analysis of volumetric data, either in the setting of a qualitative exploration, or like a guide in the qualitative measures. The speed of treatments associated with a good visualization would give the feasibility to achieve in an interactive manner, a 3D survey of a natural object. The method has been successfully applied to both synthetic and real data.

Keywords: volume rendering, implicit surface, EDT, morphologic skeleton.

INTRODUCTION

With the recent development of advanced range-imaging sensors, like x-ray CT scanner, MRI and PET modalities in medicine or Confocal Microscopy in biology, requirements for three-dimensional data visualization have increased significantly over the past several years to the point of becoming a very important issue in Computer Graphics. The basic problem in volume visualization can be defined as : given a volume data set, how extract and visualize structures contained in the volume, in a way that allows to obtain accurate analysis.

A wide variety of methods have been developed during this period, to directly reconstruct, visualize and manipulate 3D regular scalar fields. They can be classified in various ways, but usually they are grouped into two concurrently approaches : surfaces-based methods *vs.* volume-based methods.

Surface rendering methods are based on the boundary representation of the object by fitting geometric primitives to raw data [Loren87] [Oliva96] [Lucas97]. The complexity of these methods depends on the surface primitives used, and most of them owe their success for their ability to interact with 3D data sets at or near video rates. However such representations are piecewise; they lack information about the global properties of objects. Besides, they can generate a large number of primitives.

At the contrary, volume rendering methods consists in taking into account the whole data set at one time [Levoy90] [Lucas95]. Algorithms related to this category use only raw data and therefore no geometric intermediates such as polygonal meshes are necessary. These volumetric visualization modes can be subdivided into two categories, according to the projection mode used, i.e. the information carrier (using an object-order technique or an image-order technique). For object-order techniques, the visualization process, often called 'radiologic mode', is performed by integrating data along a given viewing direction according to a principle of forward mapping scheme where the volume data is mapped onto the image plane. In the latter (image-order techniques), a backward mapping scheme is used to determine for each pixel on the image plane which data samples contribute to it. At this stage, the most popular technique used to render volumetric data is the ray casting algorithm. The principle consist in sending rays from each pixel in the image plane through the volume data and determine if it intersects with the surface contained within the data.

Direct volume ray-casting is well known, and it is what the literature demonstrates, to offer the highest flexibility in terms of integrated features enhancement but often to the detriment of the time required to generate a high-quality image.

So, if we consider that volume rendering offers the same benefits as surface rendering, with several advantages (due to the uniformity and atomicity data features) like the independence to the scene/object complexity, or again the ability to represent inner information, they also generate many problems. Among these, let's mention the need of memory size, the requirements concerning processing power and especially the discrete form of 3D scene. This is the cause of many problems in voxel-based environment. Since discrete data are sampled during rendering, a low resolution volume yields high aliasing artifacts.

These observations, to state that none of those approaches presented above give complete satisfaction, are to the basis of our research. The system of visualization that we propose is a hybrid system based on the utilization of definite implicit surfaces [Hart93][Galin97] from skeletons [Bitta95]. Our objective is to finalize a tool of interactive exploration of data voxels. Us we are applied to improve two fundamental aspects bound to the generation of pictures : the speed of calculation and the quality of pictures. The research of the validation of our work while using the descended data of the real world and simulations.

We will present in the first section, some analogous works having already made the object of publications, then in the second section, our model while insisting notably on the brought optimizations. Finally, after having presented and discussed our first results, we will conclude while raising some perspectives.

PREVIOUS WORKS

The idea to use some implicit surfaces to rebuild and to visualize data acquired according to a regular grid of 3D space is a recent idea introduced by [Murak91]. Its principle consists in minimizing iteratively an energy function coding the distance between the current implicit surface defined as a blobby model (see [Blinn82]) and the raw data. The main interest of this approach resides in its capacity to represent data in a very compact way. However, processing times is too long, without intending an inaptitude to represent some complex topologies. In [Ranjan94], one recovers the same idea to directly display the object as a Union Of Spheres. Because of the small spheres created by the discrete positions of the voxels, the surface displayed from the original set of sphere does not appear smooth. One effective way to smoothen the surface in rendering is to use blended spheres.

More recently, [Bitta95] present an automatic method based on a Medial Axis Transformation to provide a robust way to initialize the shape reconstruction process. Lately, [Ferle97] present a similar method for the implicit reconstruction of branching shapes. The principle is similar to the one used in [Bitta95]. However, this approach is valid only for shapes whose skeleton express themselves in threadlike ways.

All of these works, to the exception of the first, operates according to the same principle that consists in dissociating the stage characterizing the skeleton from the one of the reconstruction from the previously established skeleton. However, and it is what we want to demonstrate in this work, this separation of tasks seems to be artificial. We think on the contrary that they are intimately bound to the point that not only results provided by the first stage are essential to the good progress of the second, for the same reason as techniques used to arrive there.

DUAL MODEL REPRESENTATION

The notion of shape is both very intuitive and imprecise. Its representation concerning reconstruction and visualization 3D passes principally again today, essentially for the historic reasons, by an polyhedral approximation of the surface, to remain under shape of a well-ordered volume of voxels.

This kind of representation is not the only. One can mention for instance, without being exhaustive :

- the representation by partitions of tetrahedrons [Berti92],
- the representation by overlapping balls [Ranja94][Attal95],
- the representation by skeleton [Attal95] [Bitta95].

These last two models have this advantage of being able to represent a compact manner shape that, *a priori*, is a pledge of efficiency. Besides, it is the main thing of our subject, the morphological skeleton presents itself currently as one of the more effective and intuitive means to represent an object, in particular a natural one. However data that we exploit are of natural origins. The surface S of such an object expresses itself in relation to its skeleton Sk(S) by the relation of

$$S = \{ p \in \mathbb{R}^3 \mid f(Sk(S), p) = \varepsilon \}$$

where f is a dependent potential function of the distance separating the p point to the nearest skeleton points and ε a constant of iso-value.

VISUALIZATION PIPELINE

The general architecture of our visualization system presents itself, as the following Fig. 1 shows, under the shape of two functional blocks.

The first, achieved only once, has the objective to characterize the studied shape with a unique descriptor : the morphological skeleton [Attal95] [Vidal96]. This skeleton must, as we will show subsequently, satisfy three essential criteria to reach the aimed objective : reversibility, homotopy, and minimality.

- the reversibility : an object must be perfectly reconstructed from its skeleton.
- the homotopy : the topology of an object must be preserved.
- the minimality : the number of the primitive describing the skeleton must be as small as possible, without contradict any other stated features.

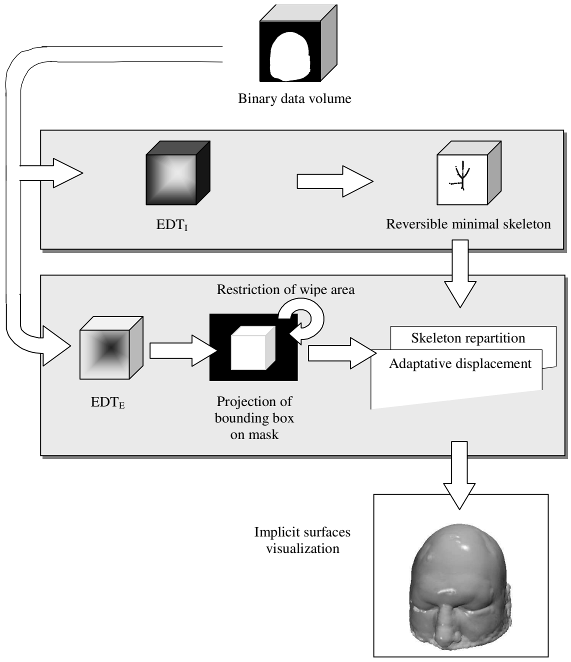


Figure 1 – General presentation of the algorithm

Besides, we get a means of relatively effective data compression, and we will have the opportunity to come back to it, because our first experimental results show that only (in the better of cases) 1% of voxels representing the object in its entirety is necessary to describe this object in totality, according to the previously stated reversibility principle.

Several stages are necessary to obtain these results. They consist of :

1. to process, from the volume of data segmented, the internal distances map to the object (EDT$_i$ for Internal Euclidean Distance Transformation) [Saito94a].
2. to evaluate a sub-set of voxels regrouping the initial object completely [Saito94b].
3. to simplify the previously obtained descriptor [Borge97].

The whole of these algorithms are based on the following skeleton definition in a continuous space :

Let Ω, a set of the E space. The open ball B(x,r) (resp. closed $\underline{B}$(x,r)) is maximal in Ω iff ∀ x', r' $B(x,r) \subset B(x',r') \subset \Omega$ (resp. $\underline{B}(x,r) \subset \underline{B}(x',r') \subset \Omega$) implies x = x' and r = r'. The skeleton of the whole Ω -put Sk(Ω) - is the geometric place of open ball centers (resp. closed), maximal in Ω.

The second block concerns the actual visualization. It admits, as input parameters, the binary data volume and its previously processed skeleton. It is based on a ray-tracer algorithm applied to voxels data volumes. The phase of displacement searching for the possible intersections between the studied object and the rays, as well as the phase evaluating the normal at the surface, have received a particular attention. The whole of these techniques are described in detail in the next section.

IMPROVING IMAGE GENERATION SPEED AND QUALITY

By optimization, we imply the ability, through the choice of a visualization strategy, to improve, in meaningful ways, the generation of pictures in terms of processing speed and picture quality. We present an original technique which makes these objectives not contradictory.

- **calculation of intersections**

Among all the techniques allowing to reduce the necessary processing time to the numeric volume visualization [Stand94] [Noord97], those based on the exploitation of distance maps permit the acceleration of calculations of intersections between the rays and the surface of the object [Zuide95]. The used principles consist of :

1. to pre-process, for all voxels outside of the object, the distance map associated with it and to substitute it to this same voxels. This stage of pre-processing uses the same transformation that the one uses to extract the skeleton. We note this transformation EDT_E, for External Euclidean Distance Transformation.

2. to exploit the distance map to sample, in a adaptive way, the positions along the ray. This displacement is done, as Fig. 2 shows, according to a step which is dependant on the distance separating the current position along the ray, of the side of the nearest object. This principle is similar in all to the one using the constants of Lipschitz to accelerate the calculation of intersections with LG-surfaces [Kalra89].

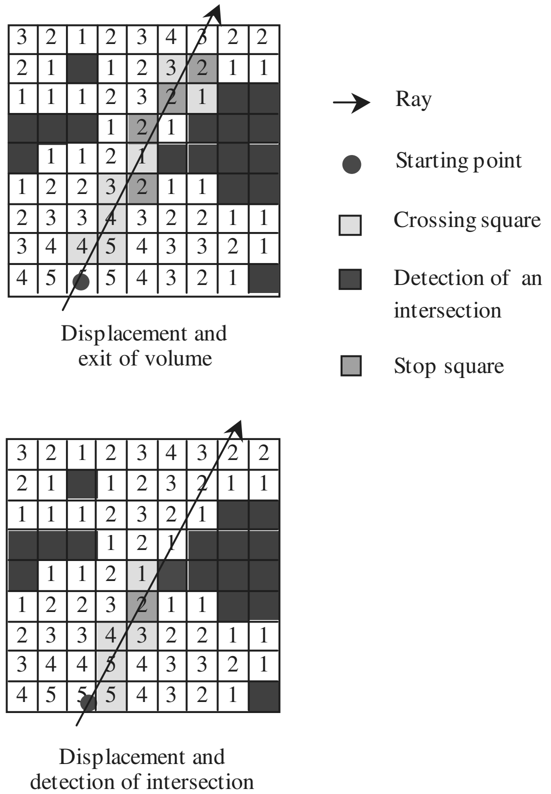


Figure 2 - Principle of adaptive displacement according to an euclidean distance map.

The evaluation of intersections to the surface of the studied object consists therefore in a succession of displacements whose length is a function of the associated distance map. To this discreet processing, we added a supplementary stage permitting to get a more precise approximation of the intersection to the surface. It consists in substituting to the discreet displacement a continuous displacement, derivative of the principle of the Sphere-Tracing [Hart96], as Fig.3 shows.

To this phase of ray acceleration, a second phase has been coupled to allow to reduce the required processing to obtain the picture. The retained principle consists in limiting the number of rays launched to those who intervene in the process of the formation of the picture. This process functions by progressive refinement of a binary mask marking pixels to value. It operates in two phases, as the following figure shows :

1. mask initialization by projection of the volume bounding box,

2. refinement of the mask for all rays meeting no object during their displacements according to the smallest distance δ met (this distance is assimilated to a sphere of radius δ, that equal a circle of radius δ' on the mask). (see Fig.4).

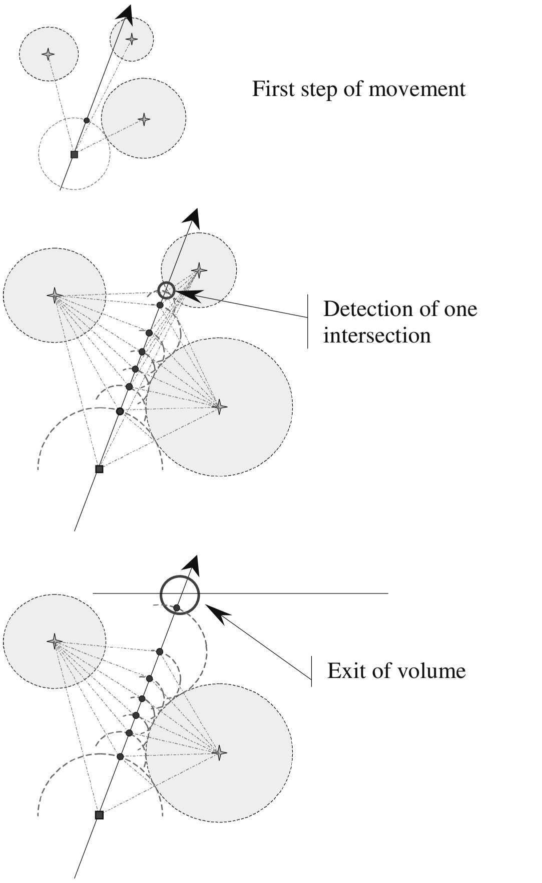


Figure 3 - Search of intersection

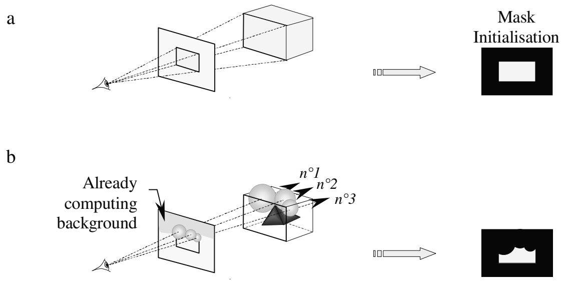


Figure 4 – Principle of mask refinement

- **quality**

The quality evaluation of the picture is a difficult task because it is completely subjective. Standard means don't exist to quantify this state, unlike other domains of the numeric imagery. For our part, we consider that the picture quality values its capacity to communicate, in a synthetic way, the main point, for its user, is the relevant information that it contains.

More concretely, and in relation to our domain of application, a way to improve the pictures quality will consist in, whether increasing the interpolation order of the gradient to the surface, so as to modify its calculation. Let's recall that the gradient of a density 3D function is defined like a partial derivative of this function, in the three directions :

$$\nabla f(x, y, z) = \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z} \right)$$

In the case of discreet data volumes, f is unknown. Therefore, this gradient could be estimate directly from data, according to the principle of definite local gradient by :

$$g(x,y,z) = \nabla f(x,y,z)$$

$$= \frac{1}{2}\left[f(x+1,y,z) - f(x-1,y,z), f(x,y+1,z) - f(x,y-1,z), f(x,y,z+1) - f(x,y,z-1) \right]$$

Another alternative consists in extending the vicinity to 26 neighbors or more. Then, a better evaluation of the gradient is got to the detriment however, performances in processing time and, consequently, additional smoothing of the surface that were not necessarily wanted.

The solution that we propose consists in substituting to this approximation of the gradient -knowledge of the discreet nature of data - a real calculation of the gradient based on the formal derivative of the polynomial P, associated with the object skeleton previously established. This process takes place after having determined the intersection points to the surface of the object rebuilt. For each of these points, all contributions of the primitive are integrated. These are the points of the skeleton participated locally to the orientation of this surface.

Therefore the skeleton is here for us, a technique to initialize a surface rebuilt implicitly by reversibility of the latter. Besides, because this skeleton is minimal, we get very effective processing times for each of normal valued. To improve them again at the step of the calculation of the above, we divide the volume in 3^3 partitions where we stock a list of atoms partially or completely overlapping each of these partitions. It allows us then to only work on a subset of the skeleton, itself already minimal.

The normal expresses itself in the following way :

$$\frac{\partial P}{\partial p} = \sum_{i=1}^{n} \left[1 - d(c_i, p) \right] \cdot k \qquad \text{with} \qquad k = \frac{1 - d(c_i, p)^2}{L + r_i^2}$$

where (c_i, r_i) represents the center and the radius of any of the components of the skeleton, L a smoothing coefficient, n the components number of the skeleton and p the surface point. The obtained pictures are presented in the following section. The necessary time of their processing is also mentioned there.

EXPERIMENTAL RESULTS AND DISCUSSION

To illustrate our algorithm of visualization, we used two types of objects. The first, represent a human head, extract from the data base of the NLM[1]. The second object is completely artificial; it consists in a combination of four spheres. All results presented here have been calculated on a HP 735 platform with 128 Mo of memory.

In order to visualize both volumes, a pre-processing is necessary which extracts their shape descriptor. This one is the reversible and minimal skeleton. Volumes characteristics are regrouped in the following table.

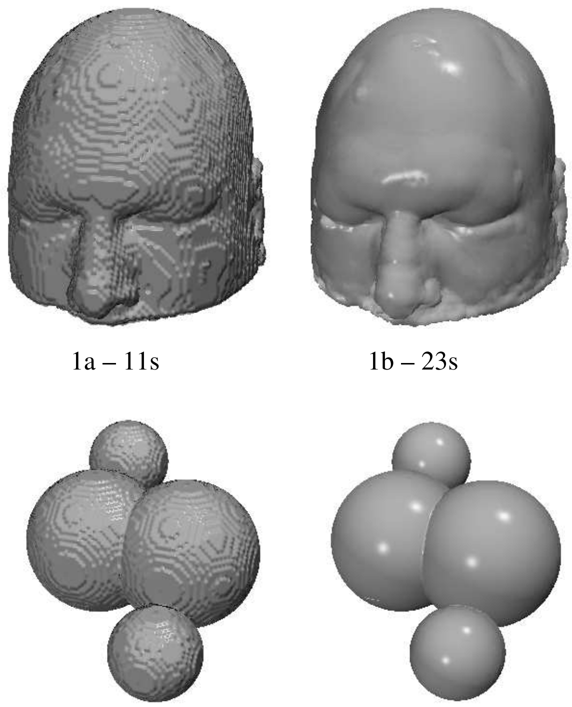
	Voxels number in object	"Object" voxels percentage in volume	Primitives number in			
			Reversible skeleton		Minimal reversible skeleton	
				% of object		% of object
Sphere	146 803	12.5 %	28	< 1 %	4	< 1 %
Head	389 615	32.5 %	10 149	3 %	1 427	< 1 %

Table 1 – Skeletons characterization

One of our objectives is the qualitative improvement of the visualization. This aspiration is achieved by the implicit surfaces and double displacement (continuous and discreet) use. All of these techniques both use the object shapes descriptor which characterizes the volume without modifying its initial form. Together, these methods solve problems coming from the domain discretization.

The first results confirm the fact that, in the most cases, the quality improvement of the processed pictures achieves to the detriment of the speed. At the phase of "discreet/continuous" displacement, the curves comparison on Fig.6 shows a very pronounced cost difference between the human head and the combination of spheres. This difference is related to the primitives number composing skeletons of every object, since the technique of displacement in continuous vision is connected intrinsically to these same primitives.

In the same way to this approach, processing speed has been optimized so that no change of quality is generated for the visualization. Thus, as Fig.6 shows, the contradiction has not failed, since these improvements surpass the loss generated by the technique of displacement. Now, we get a picture of better quality (see pictures 5-1b,5-2b) with smaller processing time.



1a – 11s 1b – 23s

2a – 10s 2b - 8s

Figure 5 - Presentation and comparison of our results in relation to the traditional approaches

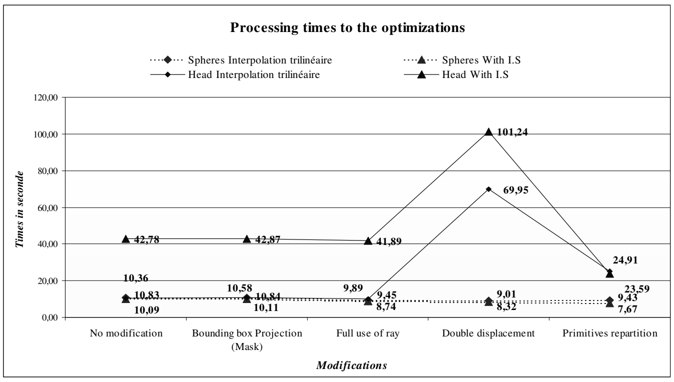


Figure 6 – Processing time according to the implemented modification

CONCLUSION

The algorithm of discreet 3D data visualization that we proposed, has two objectives to decrease the necessary processing time of a picture while improving its quality. To succeed, the retained principle is based on a dual representation of data. The use of distance maps (external and internal to

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[1] http://www.nlm.nih.gov/research/visible_human.html

the object) allows an implicit representation of the surface and provide an efficient technique for the intersections calculation. In the same way, the use of the skeleton (obtained by the internal distance map) give us also a implicitly way to rebuild the surface. The advantage of this latter, in addition its natural compactness, concern its ability to represent a shape in a continuous way according to its reversibility property.

Our first results show the relevance of our approach and lead us to consider other developments. The stage remaining even most time consuming is the calculation of the normal. Its processing time is already improved by static partitions. So a first idea would consist in substituting to this partition by a dynamic partition of octree type. This stage in processing. We consider, in the same way, the possibility to adapt the definition of the skeleton to be able to represent the shape according to different levels of details.

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