Scientific Visualization and FRep Geometric Modeling: a Survey

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Abstract

A description of the use of geometric modeling in scientific visualization is given as the basis of this brief survey. The Function Representation (FRep) providing models of both geometry and point-wise attributes is particularly considered as suitable for various applications of scientific visualization. We present applications of the described approach in visualization of physical scalar fields, geological and biological structures as well as abstract mathematical models in the form of functions of multiple variables.

1. GEOMETRIC MODELING IN SCIENTIFIC VISUALIZATION

Computer visualization of scientific data known as scientific visualization is considered a modern efficient method of data analysis. This method is widely used in different theoretical and experimental researches [1]. Its main idea is to set up a correspondence between the given data being analysed and its static or dynamic graphic interpretation, that is analysed visually, and results of such analysis are interpreted in respect to the given data. Data analysed using scientific visualization can be of different nature. The aims of analysis can be different as well. Accordingly, the corresponding graphic data can be different.

Therefore, the data analysis problem using scientific visualization consists of consequently solving the two following problems:

1) The problem of obtaining graphical images of the data being analysed (problem of initial data visualization). To obtain such an image, a spatial scene (an assembly of spatial objects) with its geometric and visual characteristics has to be put into correspondence with initial data. Then, a graphical image can be generated using some rendering procedure for further visual analysis.

2) The problem of visual analysis of the graphical image of data being analysed. This problem is solved by the user of the visualization system. Observing the obtained graphical image, the researcher can make conclusions regarding the spatial scene, spatial objects within it, their spatial relations, shapes and textures. Then, these conclusions are interpreted in the terms of the application area where the initial data came from. The process of the spatial scene analysis cannot be completely formalised. The efficiency of visual analysis is determined by the experience of the researcher and by their abilities in visual and spatial thinking. If the researcher is not satisfied by the results of visual analysis, they can repeat several steps of the visualization pipeline by tuning its parameters and in particular parameters of the spatial scene. As the result, the process of solving the data analysis problem becomes iterative and interactive.

Obviously, creation and manipulation with the spatial scene plays the key role in solving the above problems. The efficiency of such geometric modeling is determined by the functionality of available software tools.

2. FREP GEOMETRIC MODELING

In this paper, we give a brief survey of scientific visualization based on the Function Representation of geometric objects [2,3]. The Function Representation (FRep) defines a multidimensional point set (geometric object) by a single real function of multiple variables $F(X)$. Three-dimensional, time-varying and other multidimensional objects can be defined this way. In an FRep modeling system, an object is represented internally by a constructive tree data structure reflecting the logic of the object construction, where leaves represent geometric primitives and internal nodes represent operations. The function F is evaluated at a given point by an FRep tree postorder traversal procedure. The noticeable advantages of this representation are its procedural nature and extensibility, or a possibility to introduce a new primitive or operation through a small analytical expression or a short function evaluation procedure. In [4], a more general constructive hypervolume model was introduced, which supports modelling heterogeneous volumetric objects as point sets with attributes, where an attribute is a mathematical model of an object property of an arbitrary nature such as material, photometric, physical, and others assigned at every point. A hypervolume model represents a heterogeneous object by a real vector-function. More details on heterogeneous objects modeling can be found in [5].

Modeling on the basis of FRep can be performed using a high-level language HyperFun [6] and supporting its software tools. HyperFun is an international free and open source software project on FRep modeling, visualization and animation. The members of the HyperFun team, which is a freely associated group of researchers and students from multiple countries, have contributed to the application case studies described in this paper.

The HyperFun language supports all the basic concepts of FRep for constructing a single defining function for an object of complex geometry and a vector-function for a heterogeneous object. In HyperFun, the procedure for calculating the value of the function at a given point in space can be described using known constructs of the structured programming such as the conditional operator or the cycle operator, as well as special symbols for set-theoretic operations. Modeling of heterogeneous objects in HyperFun is supported by a special vector of attributes. HyperFun has the following universal features appropriate for modeling and visualization:

1. the broad and easily extensible set of geometric primitives and operations;
2. the procedural generation of geometric structures of high complexity;
3. modeling of object properties using the point attributes;
4. the visualization of isosurfaces using their piecewise linear approximation (polygonization) and raytracing;
5. possibility of using multidimensional heterogeneous objects in the visualization pipeline;

6. iterative changes of model parameters in the process of visual analysis.

The main rendering method of HyperFun is polygonization of an isosurface followed by the use of modern rendering hardware. Back in 1986, an algorithm of isosurface polygonization was proposed and implemented [7]. It is free from topological ambiguities, which are essential to the well-known algorithm of marching cubes. The trilinear interpolation inside a cubic cell and the bilinear interpolation on a cell face are used for the hyperbolic arcs detection at the cell faces and for the construction of the edges connectivity graph to resolve topological ambiguities.

Because of its advanced level of geometric modeling HyperFun can be an effective tool for scientific visualization. The works on the development of the software product HyperFun were linked to earlier works at the National Research Nuclear University "MEPhI" on the software complex SAGRAPH and its application software [8]. These products were widely used in "MEPhI" and other organizations for scientific visualization in experimental nuclear physics, physics of superconductivity and physics of protection of nuclear and physical objects, research of geological and biological structures and others.

3. SCIENTIFIC VISUALIZATION APPLICATIONS BASED ON FREP

Let us present some examples of scientific visualization applications based on FRep and HyperFun software tools.

3.1 Visualization of physical fields

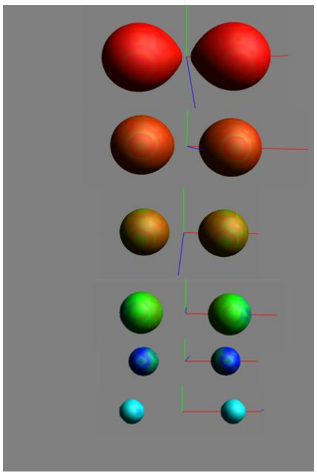
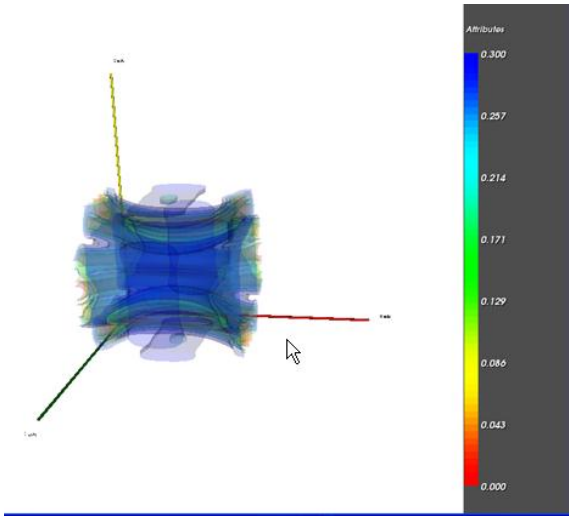
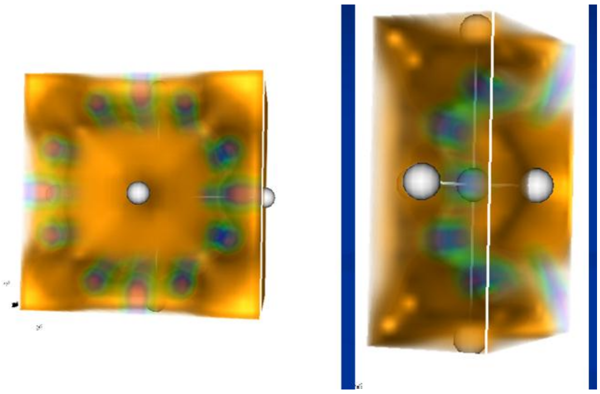


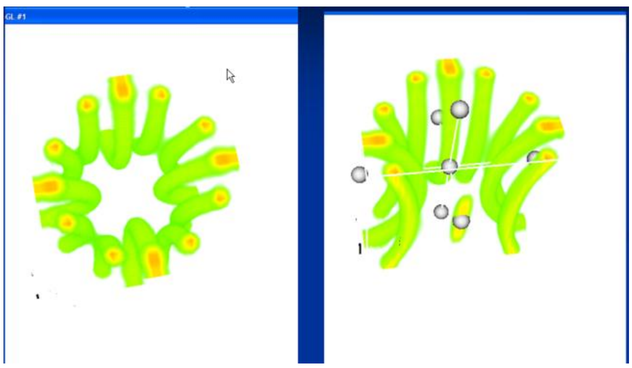
Figure 1: The electron density scalar field and electrostatic potential scalar field of the He2 molecule visualization example: a set of isosurfaces of the electron density field colored according to the electrostatic potential field values.



(a)



(b)



(c)

Figure 2: The order-parameter field for the second type superconductor (Abrikosov vortices) visualization example. Different approaches to scalar field visualization: isosurfaces (a) , volume visualization with the scalar field defined on a rectangular domain (b) and on a complex domain defined by one of the field's isosurfaces (c)

HyperFun was used as a modeling and visualization tool for analysis of physical scalar fields in the "Scientific Visualization" laboratory of the National Research Nuclear University "MEPhI". The studied scalar fields were given as functions of several variables defined on domains represented as geometric objects that also could be defined by functions of several variables. A functional description of a scalar field and its domain was obtained as the result of physical objects computer modeling within students' research work. Such description of studied physical object was presented in a file in the form of numerical data that should be analyzed.

There are two examples of scalar field visualization shown in Fig.1 and Fig.2 :

- two scalar fields visualization: the electron density scalar field and the electrostatic potential scalar field of He2 molecule (Fig.1);
- the second type superconductor scalar field visualization (Fig.2).

To obtain these results several additional file reading based primitives and attribute functions were brought to the HyperFun API and used within the resulting HyperFun model. The visualization presented in Fig. 2 was made through the VTK based interface for HyperFun.

3.2 Visualization of geological structures

Heterogeneous volumetric objects in geosciences usually consist of multiple layers of different materials with cavities, wells, and other irregularities [9]. We present here a simplified example of an FRep model of such a geological object. There are two components in such a model: the model of the point set geometry and the model of material attributes. Fig. 3a shows a volumetric geological structure with layers of different materials, cavities and an oil well.

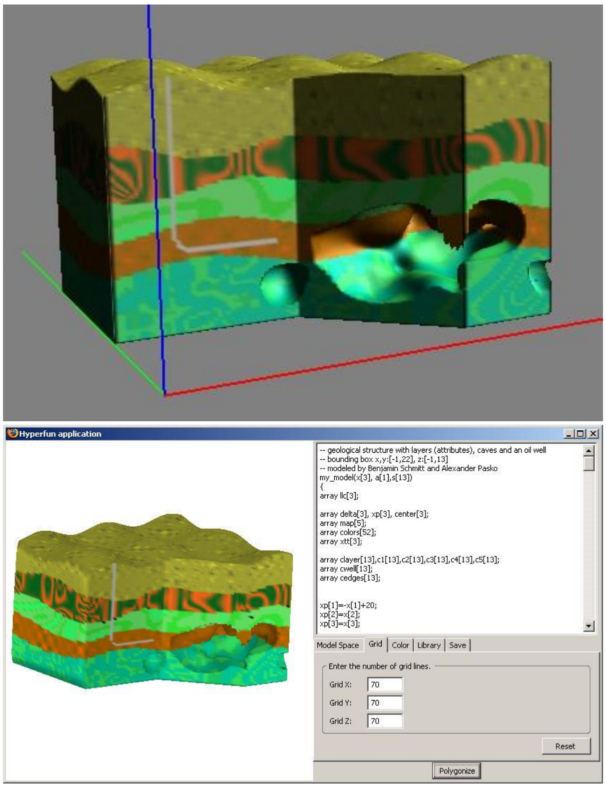


Figure 3: a) Volumetric geological structure with layers of different materials, cavities and a drilled well;
b) Hyperfox extension's visualization window with the volumetric geological model.

A Web-based modeling and visualization tool Hyperfox has been implemented within a Firefox Web browser [10]. The user interface for this tool is shown in Figure 3b. The interface allows users to define a model in the HyperFun language, set various parameters for the visualization.

3.3 Visualization of biological structures

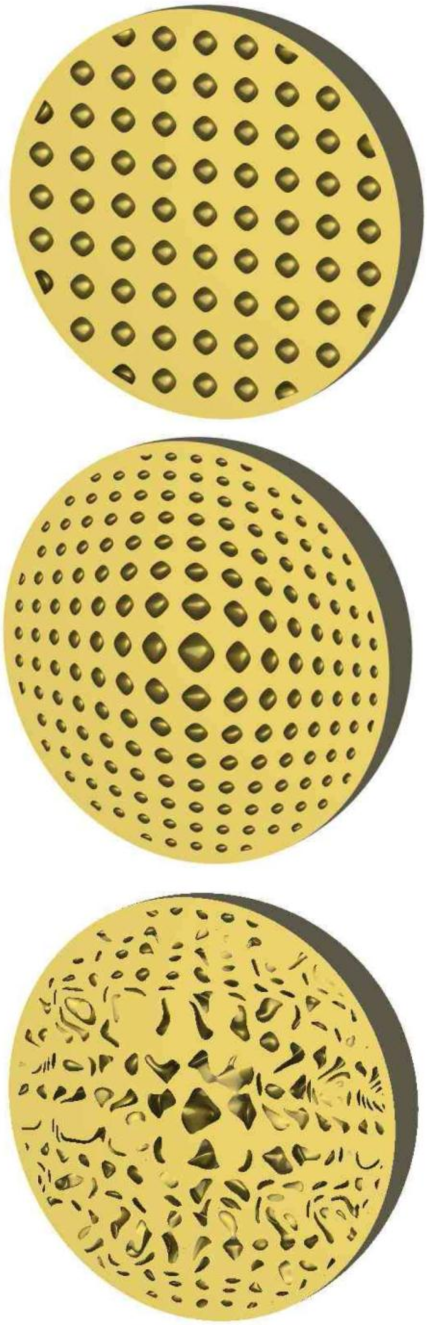


Figure 4: FRep modeling and visualization of a porous bone structure.

Irregular biological structures such as porous bones can be modelled procedurally using FRep as interconnected spherical pores with pseudo-random variations of their sizes and positions [11], see Fig. 4. The pore size is made variable depending on the distance to the surface reflecting the porous structure of bones. Such a model allows for analysis of the dynamics of diseases such as osteoporosis.

3.4 Visualization of functions of several variables

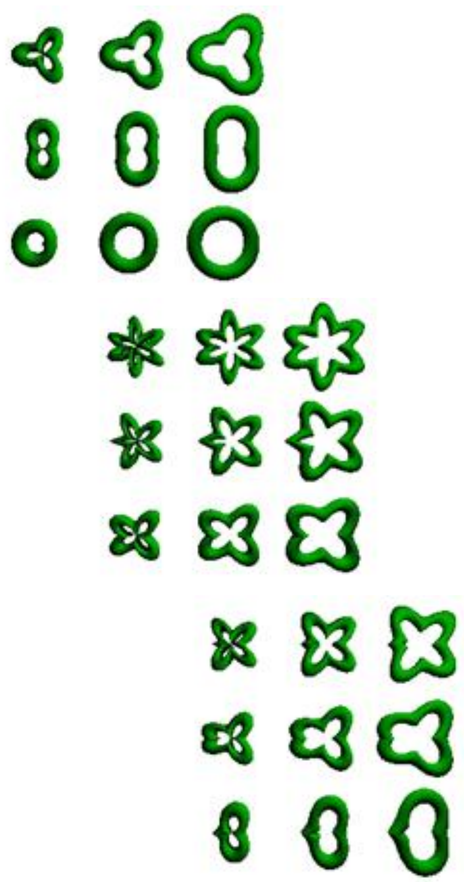


Figure 5: Visualization of a function of several variables in the form of an animated matrix of isosurfaces (three frames shown).

Visualization results of function of several variables are shown in Fig. 5. For visualization there were used matrices of isosurfaces of functions of three variables and animation was made with changes of one of variables synchronized with physical time [6].

4. CONCLUSIONS

This survey is based on the idea that the scientific visualization pipeline necessarily includes the step of introducing geometric models including volumetric and heterogeneous objects and a spatial scene before generating images. We characterize the Function Representation (FRep) of solid and heterogeneous geometric objects and the HyperFun language supporting FRep modeling. Examples of visualization in different research areas are given and illustrated, namely in physical fields simulation, studies of geological and biological structures and analysis of function of several variables. We can conclude that the experience of using FRep shows that it suits well scientific visualization in the research areas involving all kinds of scalar fields and objects with complex geometry and heterogeneous internal structures.

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