Function-based Shape Modeling Framework in Multilevel Education

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Abstract

We describe how an approach to the development of a shape modeling and visualization framework based on the rapidly progressing function representation can be used in education. The modeling language and software tools are being developed within an international HyperFun Project. We applied the theoretical framework and software tools on different levels of education starting from elementary schools to doctoral thesis research in various areas related to mathematics, computer graphics, programming languages, artistic design and animation. We illustrate the presented approach by the practical experience examples from different educational institutions and countries.

1. Introduction

One of the most rapidly developing types of shape models in computer graphics are probably implicit surfaces [Blo97] and the more general *function representation (FRep)* [PAS*95] characterized in the next section. This is due to the known problems of parametric surfaces and the boundary representation, some of which can be relatively easily solved using implicit surfaces. One of the advantages of these models is their procedural nature and possibility to introduce a new primitive or operation via a small analytical expression or a short function evaluation procedure. Experiments with new types of primitives and operations require adequate software support with the interactive input of textual definitions and redefinitions of the models without the compilation and linking steps. This was the motivation for our research group to introduce a special-purpose high-level language HyperFun [ACF*99, HF] oriented towards supporting FRep modeling. Even before its official release, the language was tested in teaching computer graphics and shape modeling at different universities. Since that time, we have devoted much effort to applications of the language and supporting tools on different levels of education starting from elementary schools to doctoral thesis research. In this paper, we describe our approach and illustrate it by the practical educational experience examples.

2. Function-based modeling and HyperFun project

The function representation [PAS*95] is a generalization of traditional implicit surfaces, Constructive Solid Geometry (CSG), and other shape models. It represents a 3D object by a continuous function of three variables as $F(x,y,z)\geq 0$, where F is a real continuous function of point coordinates. Time-dependent and other multidimensional objects are defined by a similar inequality. The function F can be easily parameterized to support modeling of a parametric family of objects. In an FRep modeling system, an object is represented by a tree structure similar to one used in CSG, reflecting the logical structure of the object construction, where leaves are primitives and nodes are operations. The function F is evaluated at a given point by a tree traversal procedure. Research results on various FRep primitives and operations can be found at the FRep Web page [SM05]. Recently, a more general constructive hypervolume model was introduced [PAS*01], which allows for modeling multidimensional point sets with attributes, where an attribute is a mathematical model of an object property of an arbitrary nature (material, photometric, physical, etc.).

In this paper, we present a number of education related applications of the HyperFun [HF], an international free and open source software project on functionally-based shape modeling, visualization and animation. Members of the HyperFun team, a freely associated group of researchers and students from different countries, have contributed to the projects described in this paper.

HyperFun [ACF*99, HF] is a minimalist programming language supporting all notions of FRep and constructive hypervolume modeling. It is a specialized high-level modeling language which allows for a parameterized description of functionally-based multidimensional geometric shapes. While being minimalist in design and easy to master, it includes all the principal programming language structures and supports all the main concepts of FRep. This language was designed to be as simple as possible in order to allow non-specialist users to create models of complex geometric shapes. In principle, the language is self-contained and allows users to build objects from scratch, without the use of any pre-defined primitives and transformations. However, its expressive power is greatly increased by the availability of the system "FRep library" that is easily extendible. Currently, the version of the FRep library in general use contains the most common primitives and transformations of quite a broad spectrum.

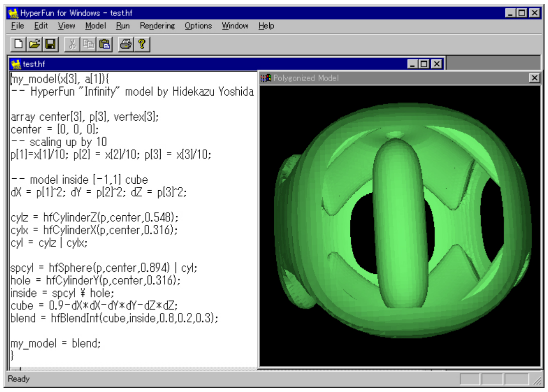

Figure 1: *Example of a HyperFun program and the corresponding image of the model in the HyperFun for Windows modeling environment.*

Let us briefly describe the following software tools that are available free of charge and can be downloaded from the HyperFun Project Web site [HF].

- The *HyperFun Polygonizer*. This program polygonizes and displays an object inputted from a HyperFun file. It has a command line interface allowing the user to define a number of modeling and rendering options. Support for higher dimensional models is also available. The program also makes it possible to output the results in VRML format.
- The *HyperFun for POVRay* is a plug-in to a popular ray-tracer POVRay (www.povray.org) which makes it possible to generate high quality photorealistic images on an ordinary PC. HyperFun objects can be manipulated as POVRay objects. All ray-tracing options are set using POVRay scene descriptions. Animation capabilities are also available.
- The *HyperFun for Windows* is an interactive system allowing the user to easy master the FRep modeling concepts using the HyperFun language while working in a conventional MS Windows environment. This program allows the user to specify an FRep model (using a built-in text editor) in the HyperFun language, to compose complex scenes with multiple objects, to specify visual parameters for subsequent rendering of various types of rendering (from simple 2D plots to animated 3D isosurfaces). Fig. 1 shows a system screenshot with a model in HyperFun language.

Special attention is paid in the project to the development of Web-based modeling tools such as the HyperFun Java applet and the interactive system EmpiricalHyperFun based on the empirical modeling principles [CAP*05]. Such tools are available on-line through a Web browser on any platform supporting Java and Java 3D. An experimental system for interactive modeling with virtual reality type of user immersion allows for the creation of a new shape through the user-controlled metamorphosis between several given shapes followed by sculpting operations for adding or removing material [ACK*05].

3. HyperFun in education

Both FRep theory and HyperFun language and software tools provide advantages for education on several levels. The primary target is mathematical education at schools and universities combined with practical experience in modeling, computer graphics, and visualization. As HyperFun is quite a simple language it can be used in teaching the basics of computer programming. In the first level (low level), all the mathematical and geometrical concepts can be hidden. At a higher level, the underlying mathematical and geometric concepts can be introduced in the courses of linear algebra and analytical geometry, computer graphics, and some specialist disciplines. Finally, at the highest level, the HyperFun language can be used for modeling shapes with complex mathematical definitions by graduate and post-graduate students in different research area (computer graphics, geometric modeling, modern interaction paradigm, Internet cooperative modeling, etc.).

Let us briefly present some educational experience in the context of the HyperFun project and then provide more specific details of teaching methods and practices.

Figure 2: *HyperFun models by a junior-high school student (top left), undergraduate university students, and a graduate student (low right).*

Summer Camps for junior high and high school students are organized at the University of Aizu (Japan). Starting from year 2000, the camp program includes three days of HyperFun exercises and a small free-form modeling project by each participant. In average, 70 schoolchildren from all over Japan attend this event. Another type of related activity is a weekend school organized by Linux Café at Chiyoda district of Tokyo. An example of a model by a junior-high school student is shown in Fig. 2 (top left). More examples can be found at
http://www.linux-cafe.jp/biz/news.html?k=4

FRep modeling was taught to and the HyperFun language was used by over than 700 university students, from the first year to the PhD levels, in Japan, Russia, United Kingdom, France, Austria, and Sweden in the following courses and exercises: computer graphics, shape modeling, visualization, computer animation, and compiler design. Examples of shape models created by students are shown in Fig. 2. More examples can be found in the gallery of the HyperFun Web site.

4. Teaching methods and practices

In this section, we present resources used in teaching, give a sample curriculum, and describe creative projects based on the use of FRep models and the HyperFun tools.

4.1. Resources

The resources used in the education process include Web sites on FRep research [SM05] and on HyperFun software development [HF], special compact disks, printed and electronic tutorials, on-line lecture notes, and repositories of student works.

Figure 3: *HyperFun CD produced for the ACM1 exhibition*

Just to illustrate this, Fig. 3 shows a HyperFun CD distributed at the educational exhibition *ACM1: Beyond Cyberspace* held on March 10-13, 2001, in San Jose, California.

There are several types of on-line tutorials for HyperFun. One is a traditional set of HTML pages available (currently in English and Japanese) at the project Web site [HF]. This tutorial provides information for relatively passive learning the basics with some included exercises. Another type for more active learning is a Web-based multimedia tutorial for the HyperFun applet (available at http://www.cgpl.org/HF/). It is a sequence of nine Macromedia Flash animations showing various aspects of practical work with the applet accompanied by an audio explanation (currently in Japanese). The first six tutorials show the use of the HyperFun Applet. A snapshot of tutorial 01 is given in Fig. 4. Note the possibilities to browse through the tutorial, to run the applet itself, to replay the animation, and to observe an image of the currently speaking tutor, who changes from page to page. The seventh tutorial is a simple exercise, however, a Cut & Paste link appears in this tutorial that spawns special window allowing copying different models from a number of more advanced exercises that are created as very simple HTML pages without Flash animation and therefore can be easily changed and customized.

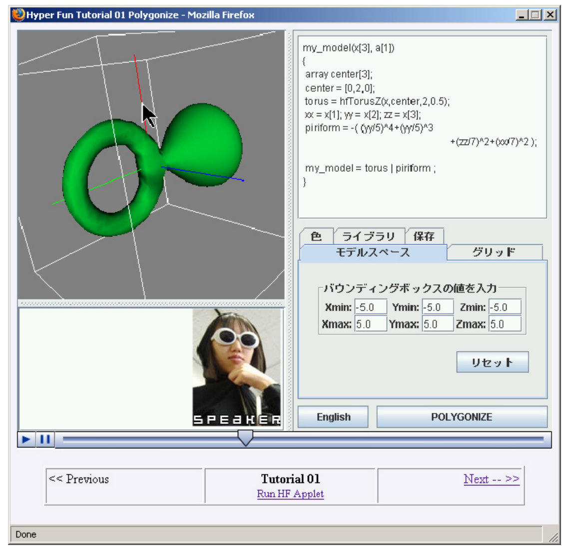

Figure 4: *Web-based multimedia tutorial on the HyperFun applet*

4.2. Sample curriculum

Let us consider, for example, the curriculum of computer graphics and animation oriented students at the Hosei University (Tokyo). In the undergraduate school, the following elective courses based on FRep and HyperFun are given:

- 1st year project class includes a set of exercises and free-form modeling of static 3D objects;
- 2nd year project class includes a set of exercises on time-dependent modeling and production of a short animation;
- 3rd year: the Visualization course with interactive exercises using HyperFun for Windows and the Computer Animation course including material on time-dependent FRep shape modeling;
- 4th year: graduation research projects include development of software tools for HyperFun or testing new models of primitives and operations using existing HyperFun software.

In the graduate school, two related lecture courses are given on "Function-based shape modeling" and "Volumetric and multidimensional modeling and visualization". Both courses include modeling projects by students. Topics of master theses include FRep related research and software development.

4.3. Creative projects

Augmented Sculpture project [ACP03] can serve as an example of a more complex and creative multilevel activity within our framework. In this project we investigate an original approach to computer-based sculpting which can be exploited not only by CG professionals but also by art student and artists. Functional representation methods actually employ constructivist techniques that allow the emulation of physical or virtual "building blocks" in the form of geometric primitive shapes that can be combined in complex spatial relationships. A computer-based means of sculptural representation along with a specific environment where the sculptural shapes are set can lead to the production of artifacts with a new aesthetic. Consequently, viewers experiencing these shapes within a virtual space can also benefit from this technology. Starting with a physical sculpture, one can create its computer model and then manipulate this model to generate new shapes that can eventually be manufactured to produce a new physical sculpture. We call this approach "augmented sculpting" as it extends the existence of physical artifacts to a virtual computer-world and then closes the loop bringing new computer models into physical existence. There is Augmented Sculpture Web Page: http://cis.k.hosei.ac.jp/~F-rep/App/ASP/FASP.html which contains all the information about the project.

The creation of the geometric models of the preexisting sculptures by Russian artist Igor Seleznev was undertaken as an exercise by computer-graphics students of the Department of Computer Science at the Moscow Engineering Physics Institute. Initially, photographs of the sculptures were made available to the students via the Web. The students were encouraged to write collaboratively and share the HyperFun code to create the rough prototype geometric models. They then formed groups of two or three to combine their efforts in building more accurate models. The physical sculptures were made available to the students at this stage, and the artist himself took part in assessing and discussing the intermediate results with the students, both in person and through the Internet. Finally, the students constructed geometric models of the sculptures in the form of a HyperFun language program, as well as a set of photorealistic renderings of the sculptures using the same program. Note that the sculptures have quite complex shapes with subtle non-regular features, and students could see benefits from using such advanced primitives as convolution surfaces.

Model building and debugging was carried out using the HyperFun for Windows toolkit, and the students generated the final ray-traced renderings using the HyperFun for POVRay toolkit. For example, students P. Yablochkin and N. Varivoda, starting from a real bronze statuette "Gymnast" (Fig. 5a), created its model in Hyperfun language (its ray-traced image is shown in Fig. 5b). Then another student A. Ogarko has modified that model to make it time-dependent that allowed him to generate an animation (three frame of Gymnast animation sequence are shown in Fig. 6). The entire animation sequence is available at the project Web page.

a b

Figure 5: *(a) real sculpture; (b) HyperFun model;*

Figure 6: *Three frames of the Gymnast animation*

a b

Figure 7: *(a) models of three sculptures produced by a RP machine; (b) RP model of the "triangle metamorphosis".*

Having created models of a few sculptures one can implement a metamorphosis between them thus generating very interesting sculpting artifacts. Traditionally, metamorphosis is a complex problem that requires the animator to establish a set of correspondence between the initial and final key shapes. In the FRep framework, metamorphosis is performed almost trivially by a non-specialist user and can generate intermediate shapes by interpolating between more than two key ones. Having created such artifacts one can then produce their physical incarnations using rapid prototyping machinery and the process called '3D printing'. Fig. 7 shows artifacts produced by students of the Hosei University in Tokyo using a SLA3500 rapid prototyping (RP) machine. Three original sculpture models ("Gymnast", "Naked" and "Walking Androgynous") are shown in Fig. 7a and the result of the metamorphosis is shown in Fig. 7b. Note that the students in Tokyo used so-called "triangle metamorphosis" between the models of three sculptures created by Moscow students!

The next stage is using the experimental interactive modeling system mentioned above. This system allows the artist to navigate interactively through a so-called 'FRep Sculpture Garden', which is a time-dependent scene composed of multiple objects. So, the artist experiences an immersion into a virtual space where he or she can generate new shapes using metamorphosis between the sculptures. Editing the shapes on the fly by adding or removal material is also possible. This is a base for an interactive art installation in which physical and virtual artifacts are combined and overlaid [ACP03, A*05]. Such a project allows professionals, artists and students to mix and work together thus encouraging them for exchange of ideas and skills.

5. Discussion and conclusion

Existing interactive shape modeling systems in CAD and animation typically provide sophisticated multilevel graphical user interfaces (GUI). The ease of using menus and buttons creates the illusion of the easiness of modeling itself. However, the use of GUI leads to alienation of the user from the model being constructed. As the result, the educational process is concentrated on the details and specifics of GUI instead of the specific characteristics of the model. The reason of such developments is high complexity of the current shape models such as parametric surfaces and their combination into boundary representations, which prohibits direct interaction of the end user with the data structures because of the high risk of getting inconsistent or false models.

Another level of creating shape models consists in development of application programs based on so-called application program interfaces (API) such as ACIS (Spatial Technology), Parasolid (UGS), or SvLis (Bath University). APIs provide complete access to all components of the shape model, but require extensive knowledge in the underlying mathematical model and data structures, as well as in the programming language of the API embedding.

In the context of our framework, we propose to apply in education the rather general mathematical model covering wide range of shapes, but simple enough to be mastered by a non-qualified user with minimal preparation time. In contrast to the existing interactive modeling systems, the HyperFun model is the text of the script the student is directly editing and redefining. The FRep model and supporting HyperFun software tools allow for the student to access and modify any detail of the shape as with using APIs, but the same time keeping the ease of interaction similar to the level provided by GUIs. Note also that using mathematical expressions for constructing shapes encourages students to deeper understanding the underlying theory. At the same time that mathematical theory, when hidden in the library primitives and operations, does not prevent non-specialist users, including schoolchildren and artists, from exploiting benefits of very modern and sophisticated computer graphics methods.

Acknowledgements

We are grateful to all the members of the HyperFun team for their everyday help and support. The example images were produced by students Hidekazu Yoshida, Katsuro Masato, Irina Mijiritskaya, and Tatsushi Someya. The HyperFun online interactive tutorials were created by the Computer Arts Laboratory of the University of Aizu in Japan, Mitsuhiro Aita is the producer and Naomi Oouchi is the artistic director. The HyperFun CD artworks were produced by Turlif Vilbrandt.

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